Nuclear Engineering 282, UC Berkeley

Charged Particle Sources and Beam Technology

Beam Diagnostics +Stability

Christoph Steier

Lawrence Berkeley National Laboratory
Accelerator and Fusion Research Division

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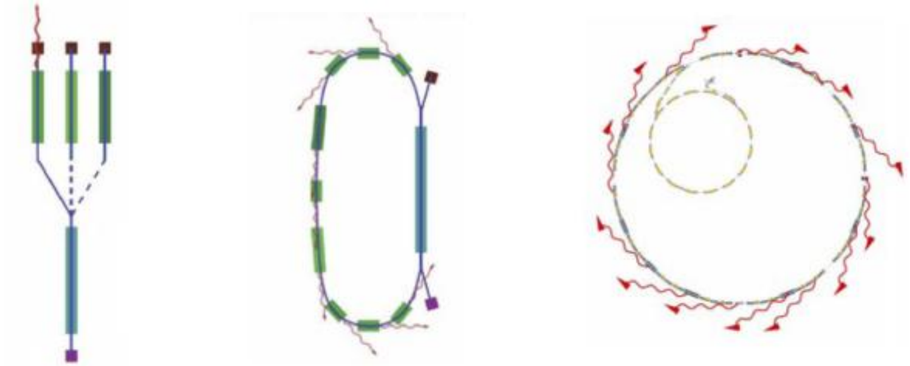
Topics

- Quick Recap of Future Light Sources
  - —Fundamental Features of 3 Approaches
- Beam Diagnostics
  - —Beamsize
  - —Beam Position
- Stability
  - —Design
  - —Feedback Systems
- Summary

Lectures are posted at
http://als.lbl.gov/als_physics/robin/Teaching/NUC%20282c.html

Recap - a variety of synchrotron radiation source concepts to pursue

- **(Ultimate) Storage rings**
- **Energy recovery linac (ERL)**
- **Free electron laser (FEL)**
- Laser wakefield accelerator
- Optical manipulation of electron beams



Figures of merit

- Average and peak flux
- Average and peak brightness
- Pulse repetition rate
- Temporal coherence
- Bandwidth
- Spatial coherence
- Pulse duration
- Synchronization
- Tunability
- # beamlines
- Beam stability

Future generations of light sources will likely utilize novel techniques for producing photons tailored to application needs

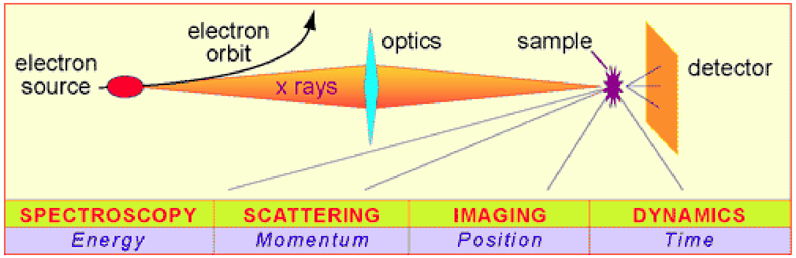
Different operating modes

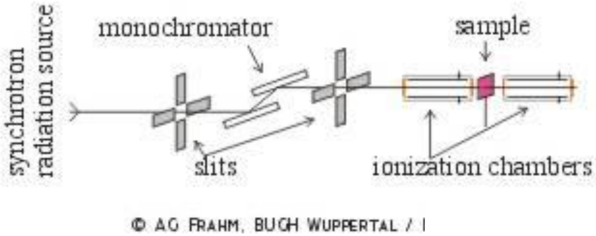
Different facilities

Motivation (Beam Diagnostics)

- If you ever have to design, optimize or understand a beam transport, accelerator, ring, … you need to understand the main concepts of acceleration/longitudinal beam dynamics, transverse dynamics, …
- To optimize machine performance, one has to measure many quantities
  - Direct measurements
    - Position, beamsize, …
  - Indirect measurements
    - beta functions, tune, dispersion, momentum compaction factor, …
- Main motivation for precise beam measurements
  - No complex system is in the right state from the start.
    - Have to understand/debug/correct it
  - System also does not stay in its optimum condition
    - Stability requires constant correction.

Motivation





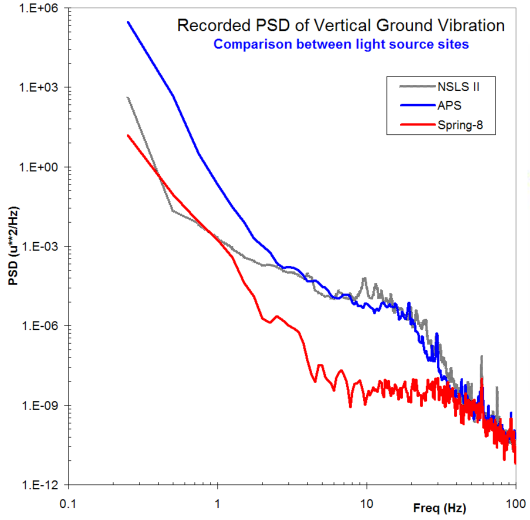
Typical requirements of modern SR user experiments:

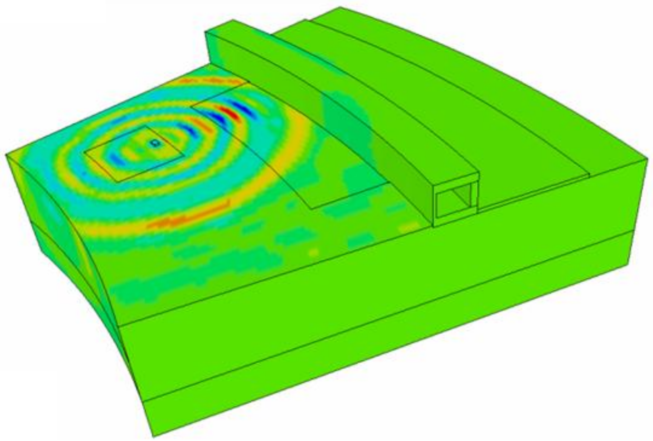
Measurement parameter	Stability Requirement
Intensity variation ΔI/I	<<1% of normalized I
Position and angle	<2-5% of beam σ and σ’
Energy resolution ΔE/E	$<10^{-4}$
Timing jitter	<10% of critical time scale
Data acquisition rate	$10^{-3} – 10^{5}$ Hz

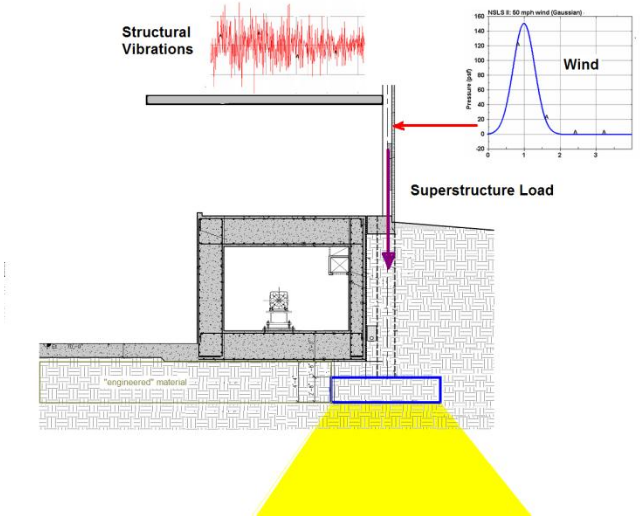
Adapted from B. Hettel

- **All of those requirements relate back into stability requirements for beam position + angle, beamsize + emittance, beam energy, beam energy spread, …**
- **Often stability can be more important to SR users than brightness+flux**
- **For current SR sources, this means for example submicron orbit stability (for ERLs in both planes)**

Stability / Design



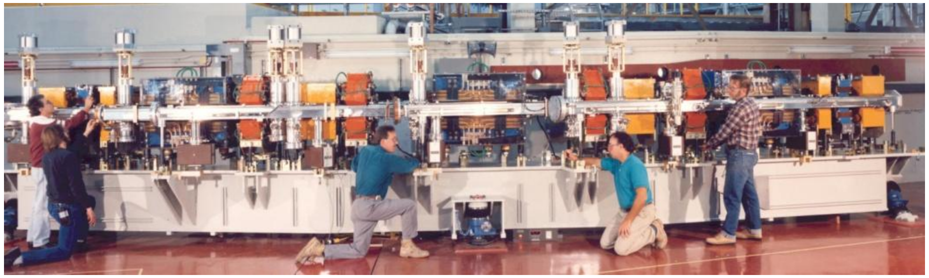




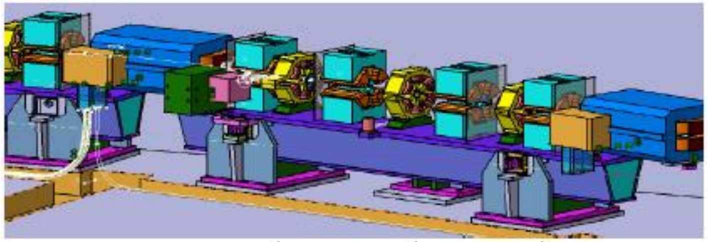
Courtesy: N. Simos, NSLS-II

- **One hopefully starts by selecting a good / quiet site (not always possible) - at least need to know all caveats**
- **Nowadays FEA allows optimization of slab design**
- **Important: Minimize vibration coupling from pumps, …**
- **Also keep external disturbances in mind (wind, sun, …)**

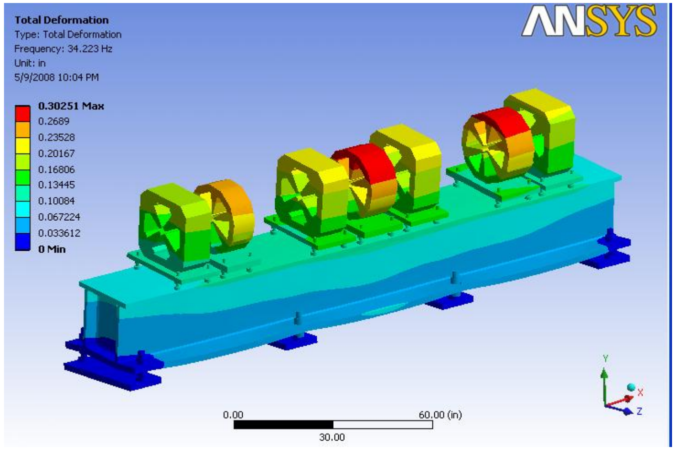
Girder Design



ALS



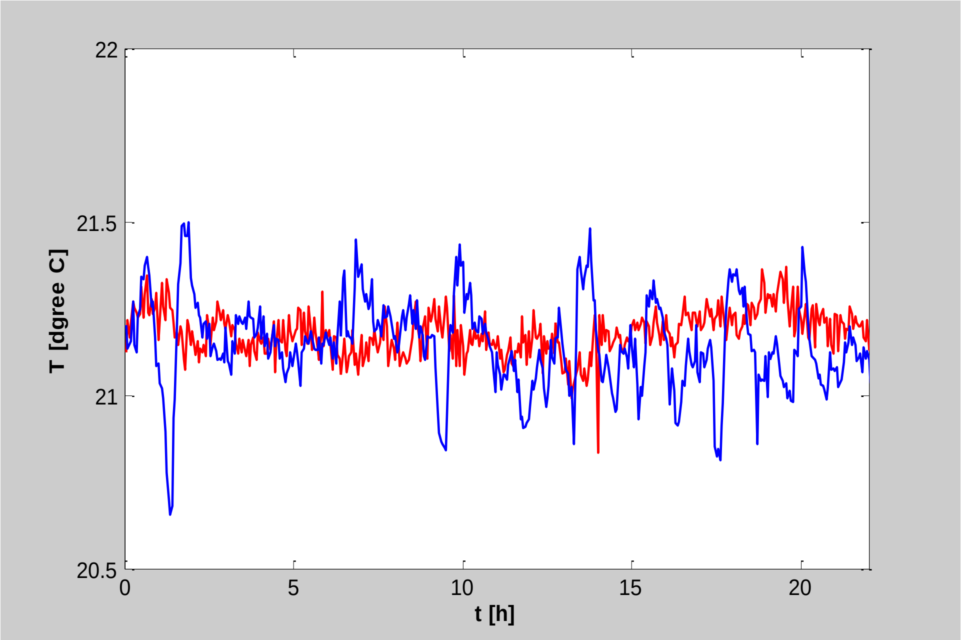
Soleil

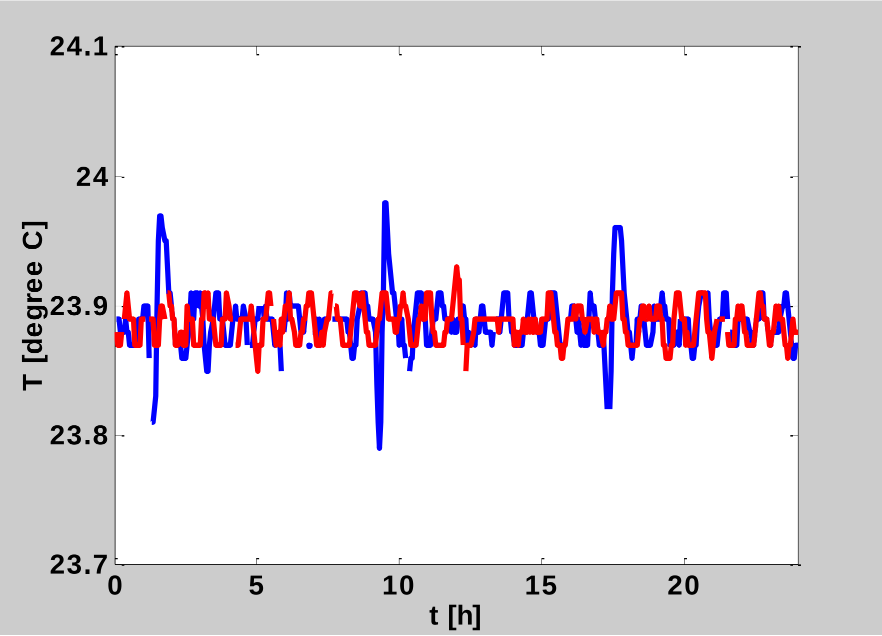


NSLS-II: courtesy S. Sharma

- **Some early 3rd generation sources had massive girders (low resonance frequencies – sampling larger ground oscillation amplitudes)**
- **Later ones had girders with higher resonance frequencies but movers, that significantly lowered them**
- **Latest designs (Soleil, NSLS-II) avoid this caveat – smaller vibration transmission to beam**

Air/water temperature stability

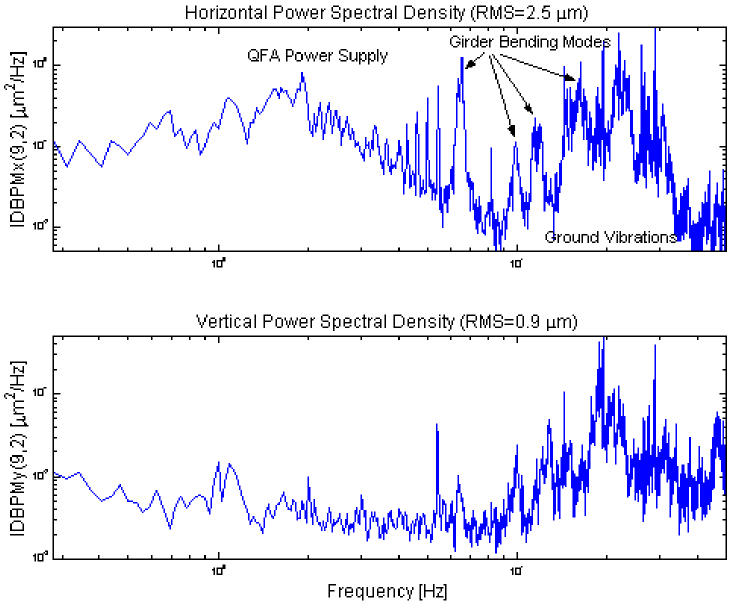




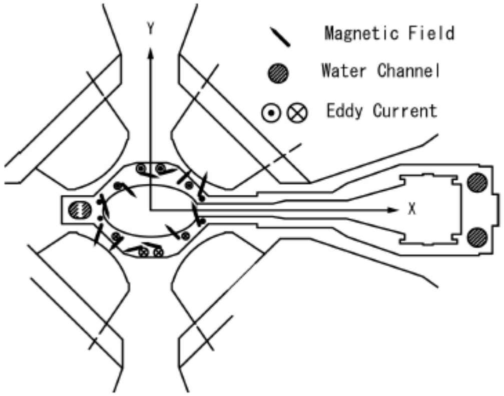
Left: ALS LCW temperature, Right: Tunnel air temperature (red – with top-off)

- **Stable environmental conditions are extremely important**
- **State of the art is water and tunnel air temperature stability on the order of 0.1 degree C**
- **Stable power supply controllers, invar rods for BPM mounts, … also help, but it is always best to also keep the conditions constant**

Improvement after construction



Data taken on 12-12-1999, during a 1.9 GeV user run at 278 mAmps



Eddy Current made by Q-mag. field kicks the electron beam.

S. Matsui, et al. Jpn. J. Appl. Phys. Vol. 42 (2003) pp.L338

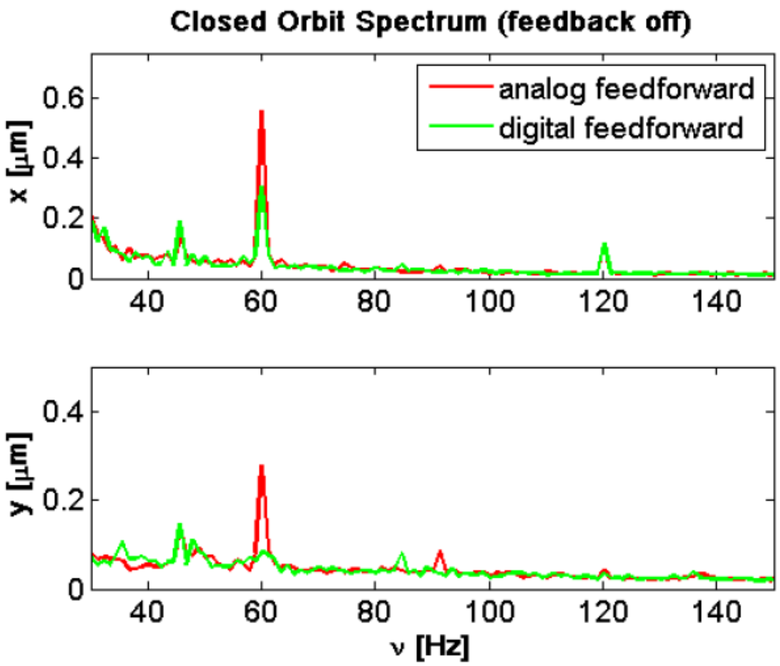
ALS – fixed power supply

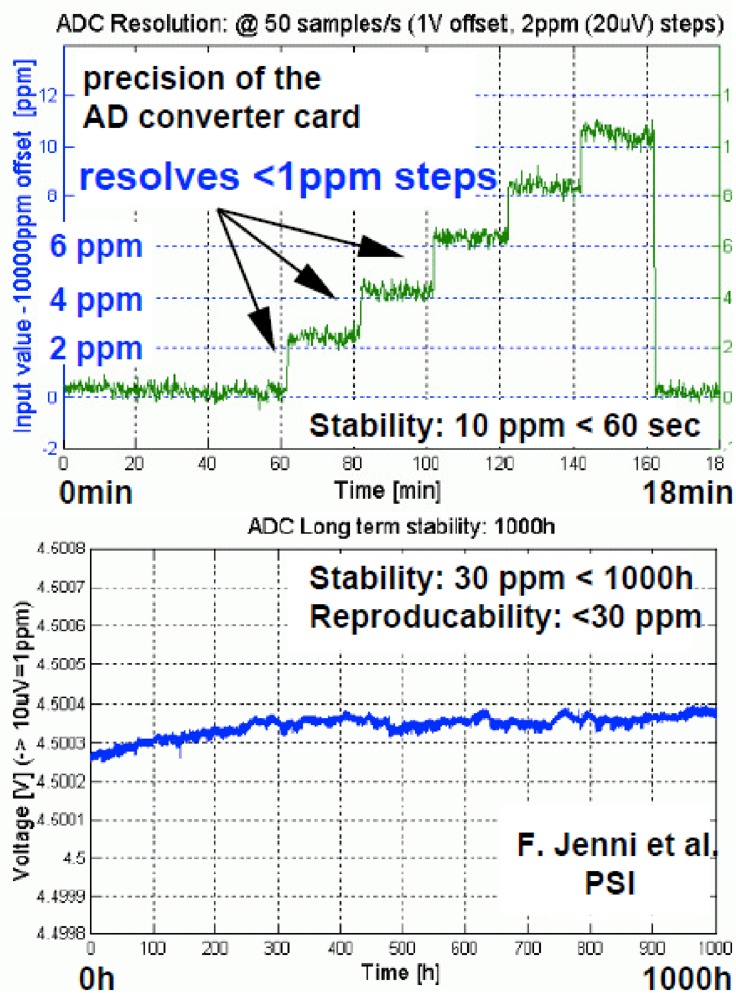
Spring-8: water vibration

- **Often vibration sources / coupling into sensitive equipment is found during after commissioning**
- **Fixing the worst offenders often gives big benefit**
- **Examples above: Power supply at ALS, water induced vacuum chamber vibration at Spring-8; Another example are viscoelastic damping elements at ESRF**

Good power supplies are essential

- Strong corrector magnets with high vacuum chamber cut off frequencies can be significant sources of orbit noise
- Observed at several light sources
- Achievable power supply performance increased over the years



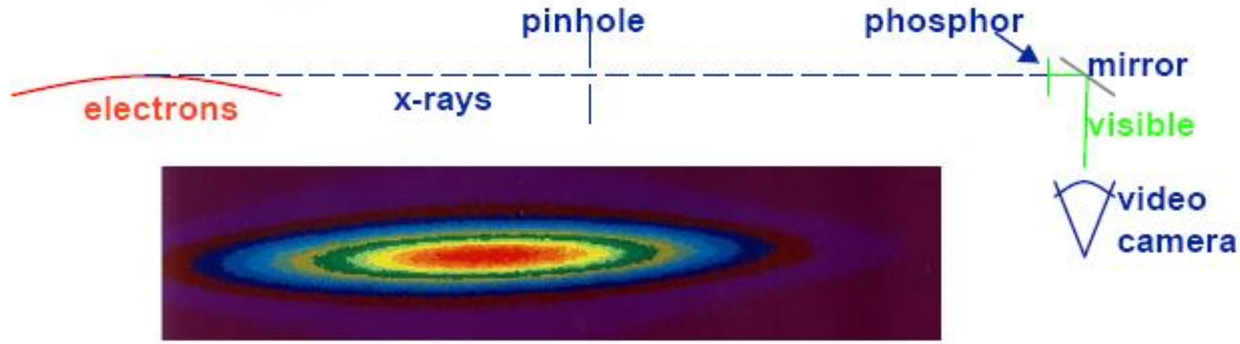


Beam Diagnostics: Beamsize, Emittance

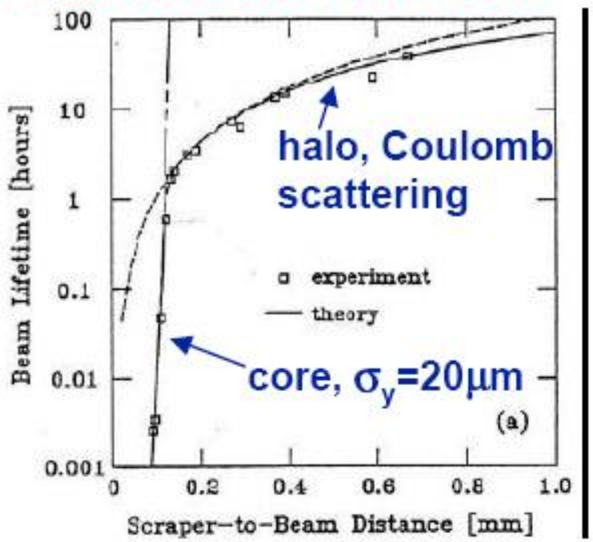
- Size measurements can be done many different ways …
  - Imaging synchrotron radiation
  - Measuring residual gas ionization profile
  - Scanning wires, collimators, laser …
  - Screens (fluorescent, transition radiation,…)
  - Using interferometry
  - Measuring indirect quantities
    - (lifetime, beam-beam deflection, …)
  - Measuring higher (quadrupole+) moments of electromagnetic field co-propagating with beam
- Some methods (pinhole arrays) allow simultaneous measurement of size and divergence $\rightarrow$ emittance.
- Other ways to measure emittance:
  - measuring simultaneously at different places
  - changing the optical functions in a controlled way
  - measurements of lattice functions in addition to size

Beam Size Measurements

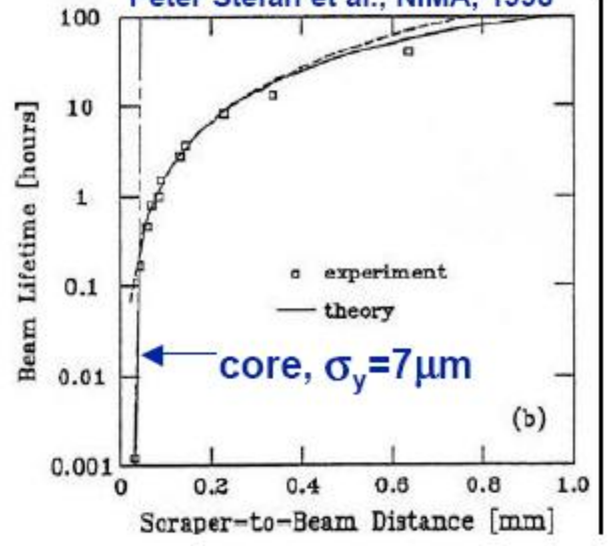
Synchrotron light monitors measure beam core



Scrapers measure beam halo

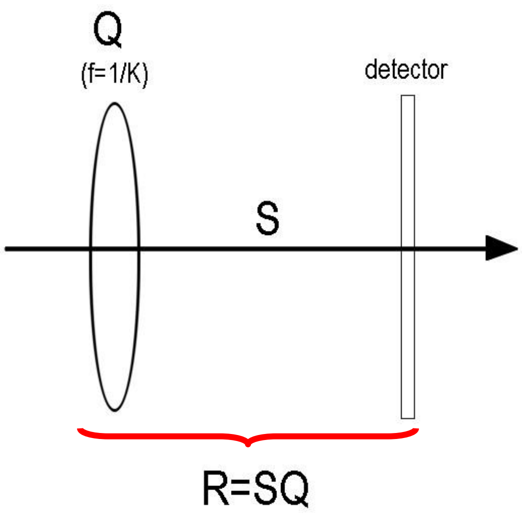


Peter Stefan et al., NIMA, 1998



Measurement of the Transverse Beam Emittance

Principle: with a well-centered beam, measure the beam size as a function of the quadrupole field strength



Here
Q is the transfer matrix of the quadrupole
R is the transfer matrix between the quadrupole and the beam size detector

With $Q = \begin{pmatrix} 1 & 0 \\ K & 1 \end{pmatrix}$ then $R = \begin{pmatrix} S_{11} + KS_{12} & S_{12} \\ S_{21} + KS_{22} & S_{22} \end{pmatrix}$ with $\Sigma_{\mathrm{beam}} = R\Sigma_{\mathrm{beam},0}R^t$

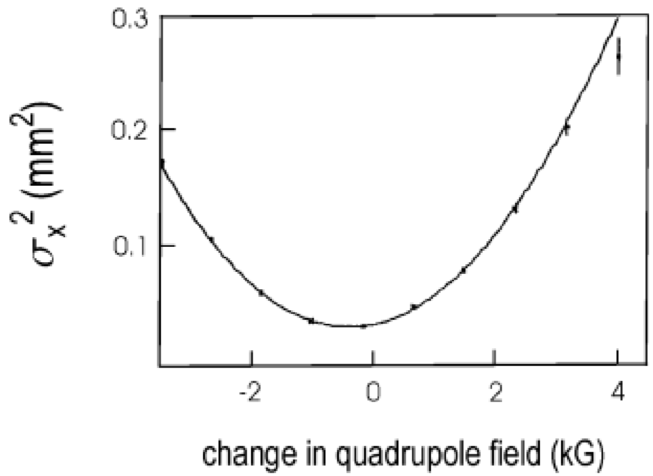
The (11)-element of the beam transfer matrix is found after algebra to be:

$$\begin{aligned}\Sigma_{11}(= \langle x^2 \rangle) &= ({S_{11}}^2 \Sigma_{11_0} + 2S_{11}S_{12}\Sigma_{12_0} + {S_{12}}^2\Sigma_{22_0}) \\ &+ (2S_{11}S_{12}\Sigma_{11_0} + 2{S_{12}}^2\Sigma_{12_0})K + {S_{12}}^2\Sigma_{11}K^2\end{aligned}$$

which is quadratic in the field strength, K

Measurement: measure beam size versus quadrupole field strength

data:



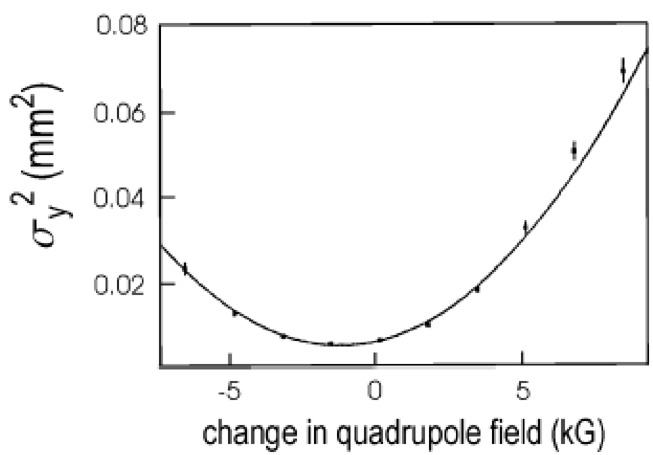
fitting function (parabolic):

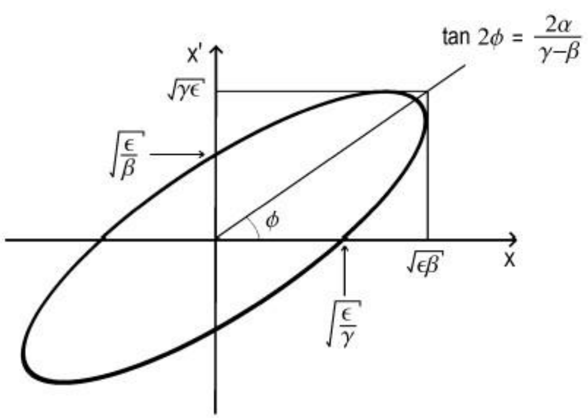
$$\Sigma_{11} = A(K-B)^2 + C$$
$$= AK^2 - 2ABK + (C + AB^2)$$

And finally for the emittance:

$$\epsilon_x = \sqrt{AC}/S_{12}^2$$

In fact one can reconstruct twiss functions:





Fundamental Limitation: Diffraction

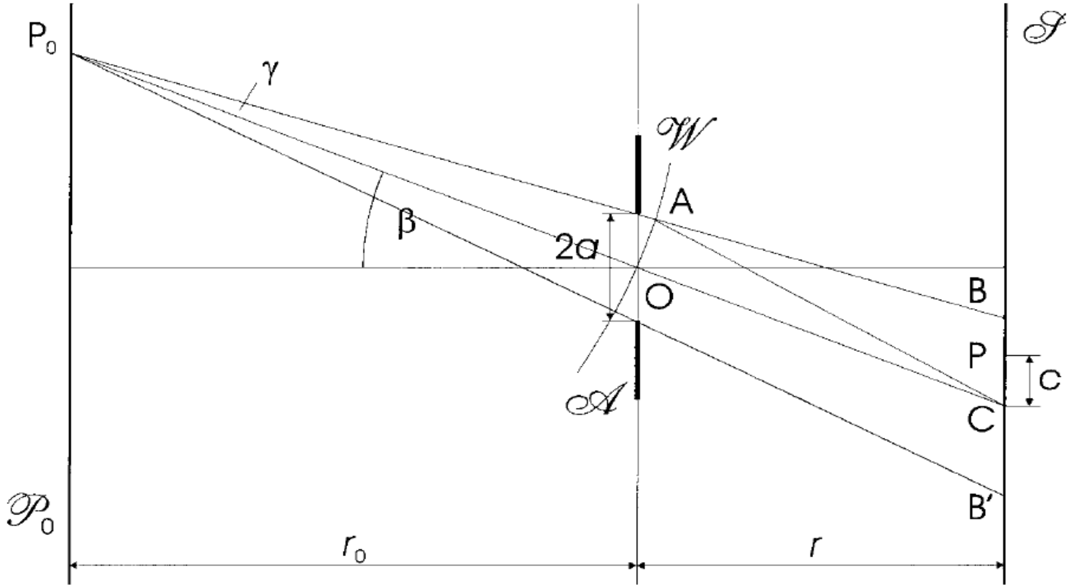
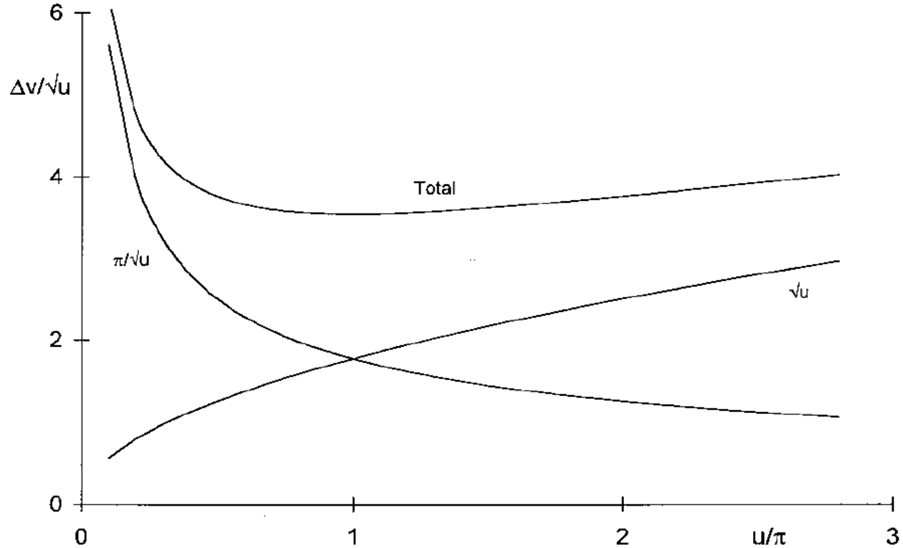


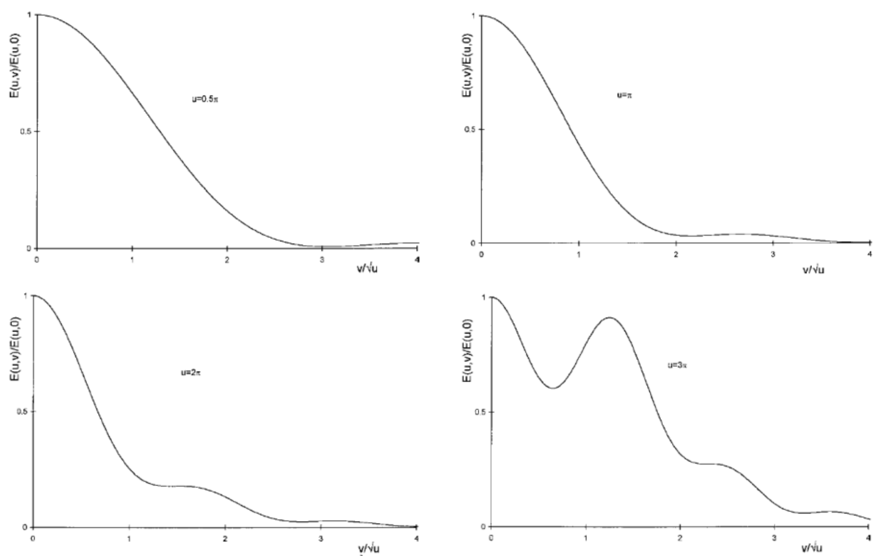
Fig. 1. Lensless imaging by a circular aperture $\mathscr{A}$ of diameter $2a$. $\mathscr{P}_0$ = object plane, P_0 = object point, O = aperture center, $\mathscr{S}$ = screen, BPCB' = geometrical image, $c = PC$ = radial distance from image center.

$$v = \frac{2\pi a c}{\lambda r}, \quad u = \frac{2\pi a^2 (r_0 + r)}{\lambda r_0 r}$$

- **If you have a pinhole lens (or a finite size lens, mirror, beamline aperture) – diffraction is an important effect**
- **Causes widening of image for small apertures or long wavelengths (diffraction patterns/rings)**
- **This limits us to using x-rays to measure small beamsizes using synchrotron radiation**

Diffraction II

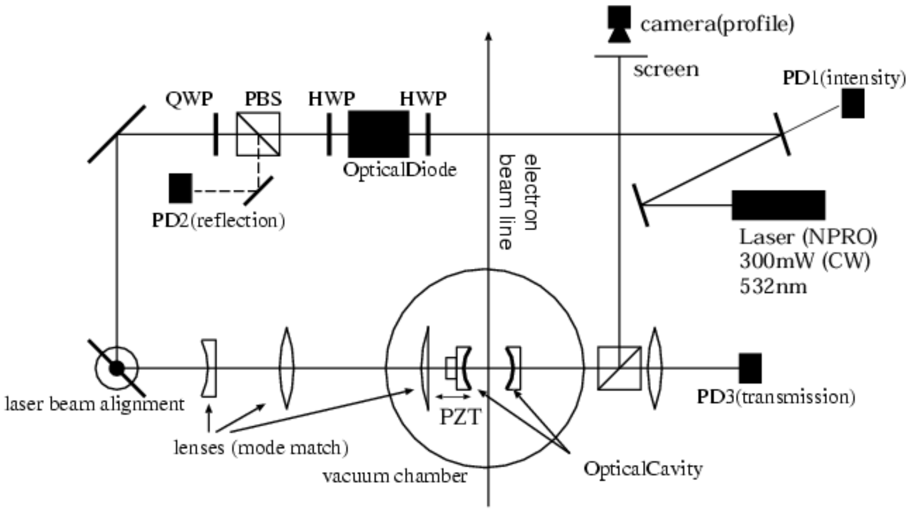


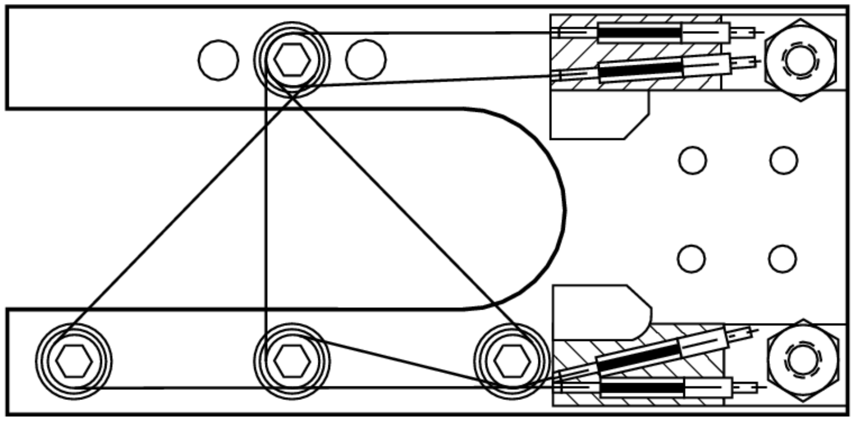


- Top: Broadening of image as a function of normalized hole size due to diffraction and geometeric effects as well as total broadening (simplified Petzval's estimate) – diffraction limit at u = π
- Right: Diffraction profiles for different values of configuration parameter u
- Conclusion: Want to use a small hole size, but that also requires using small wavelengths. At ALS: pinhole size about 10 microns, photon wavelength about 0.5 Angstroem.

Wire Scanners/Flying Wires/Laser Wires/Screens

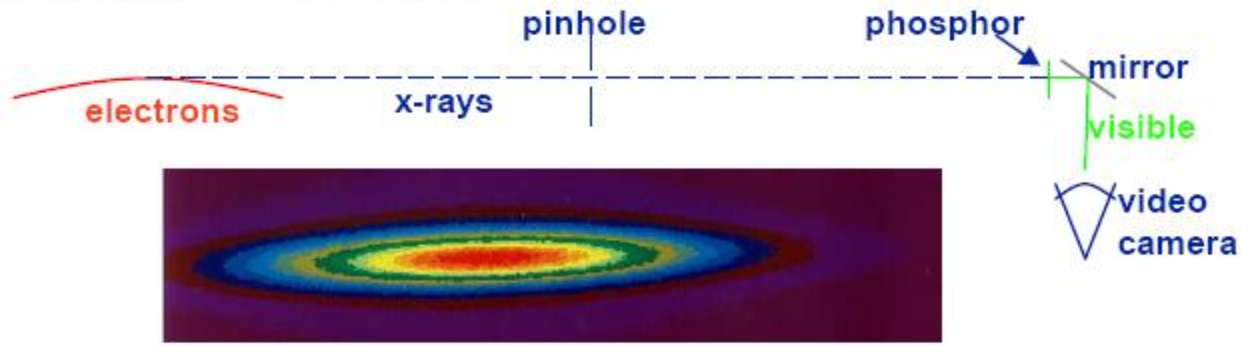
- Wire Scanners (SLAC/SLC) and screens are mostly used in beamlines and Linacs. Can achieve resonable high resolution but are usually destructive. Both can measure position and profile.
- Flying wires are less destructive and laser wires (KEK/ATF) are minimally destructive and provide excellent resolution (however they are slow)
- Some laser or interferometer based schemes achieve nm type resolutions.



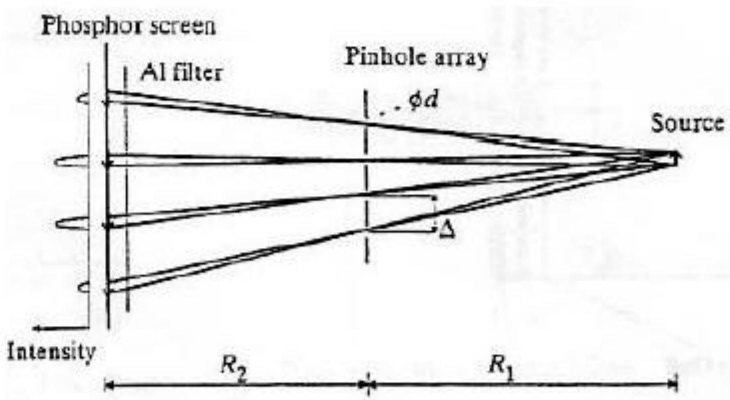


Pinhole cameras

X-Ray pinhole camera



Pinhole camera array
(Kuske et al., Bessy)



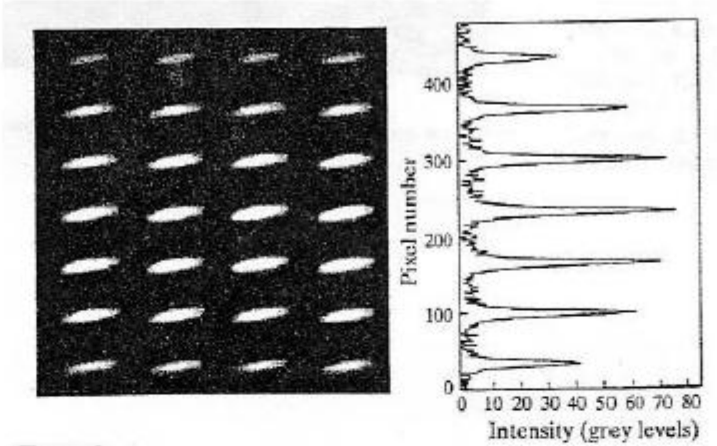
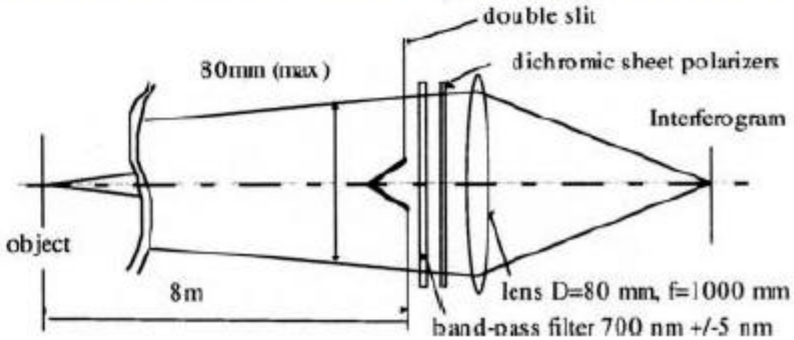
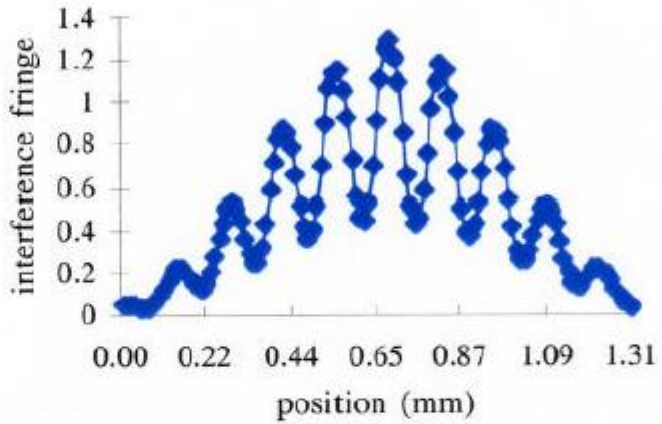


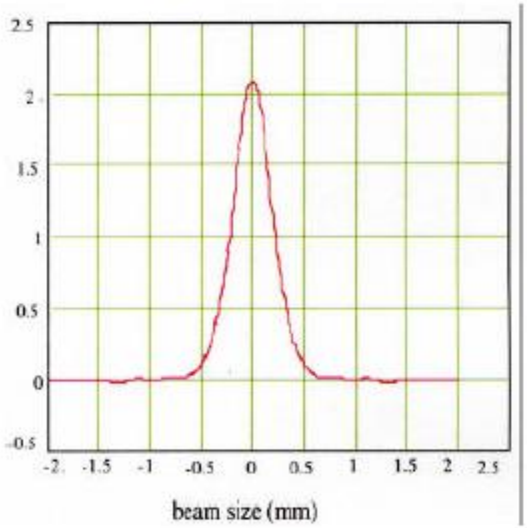
Figure 2
Left: image of a portion of the phosphor observed on a BESSY I bending magnet. Right: integrated intensities of one column of images on the phosphor.

Interferometry can help to bypass diffraction limit

Michelson's method for measuring the size of stars applied to measuring electron beam size. Spatial cohence increases as beam size decreases.







← Vertical beam size can be obtained from the Fourier transform of the degree of spatial coherence.

Mitsuhashi, PAC 97)

Beamsize Stability

- Because orbit stability is excellent, at ALS we actually receive more complaints about beamsize stability
- Problem is tougher at low energy light sources (beam less stiff)
- Main culprit at ALS are EPUs (elliptically polarizing undulators)
- Some examples of affected experiments:
  - — STXM (scanning transmission X-ray microscopes) – I0 normalization difficult, not included in state-of-the-art beamlines
  - — Microfocus beamlines investigating dirt samples

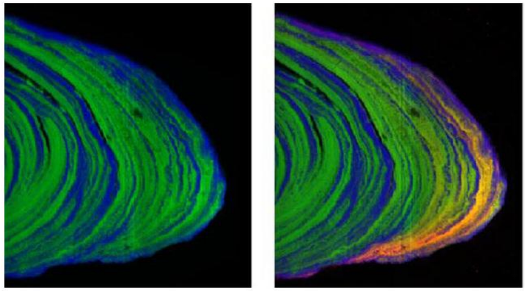
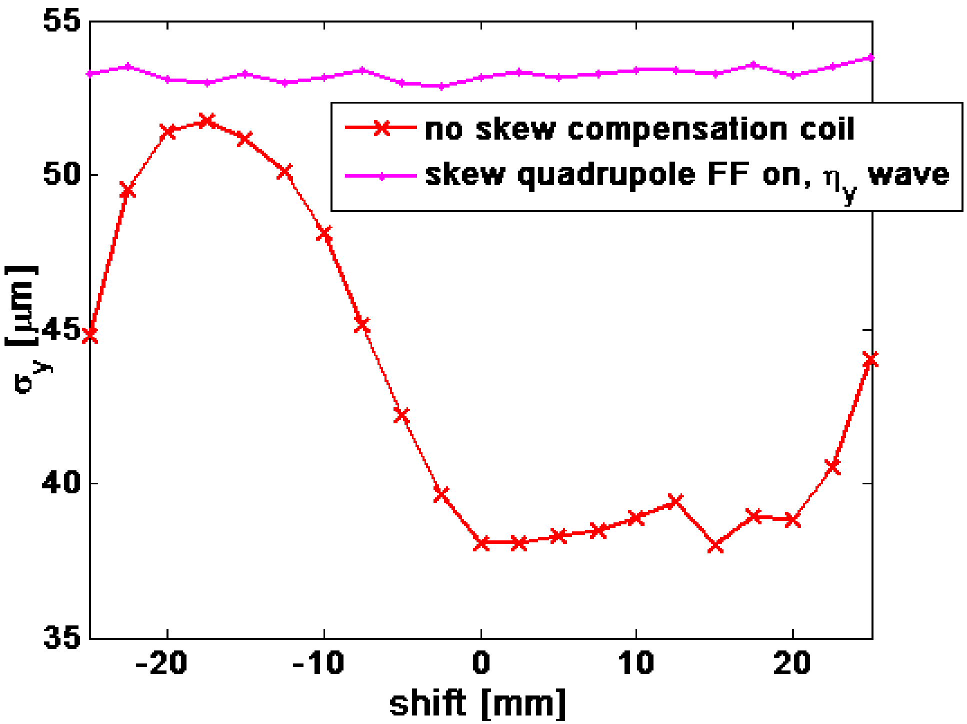


Figure 1. Synchrotron-based micro-X-ray radiation fluorescence (µSXRF) Fe and Mn maps of the outermost Fe and Mn layers of a ferromanganese nodule from the Baltic sea (6600 µm x 3780 µm, step size 15 µm, counting time 250 ms/pixel, red = Zn, green = Mn, blue = Fe, beamline: 10.3.2.). The onion-like structure of growth rims is clearly discernible as few hundreds µm thick Fe/Mn-rich bandings. Zn is exclusively associated with Mn, as indicated by the orange color of the Zn-containing Mn layers, and its concentration increases towards the surface.

- What needs to be corrected:
  - — Optics distortion (beta functions)
  - — Skew gradients
  - — Potentially horizontal/vertical natural emittance

Undulator effects on vertical beamsize

- Vertical beamsize variations due to EPU motion were big problem.
- Is caused by skew quadrupole (both gap and row phase dependent)
- Root cause reduced in newer devices
- Installed skew coils for feedforward correction
- Stability now <1%, relative stability will at first be worse for smaller beamsizes

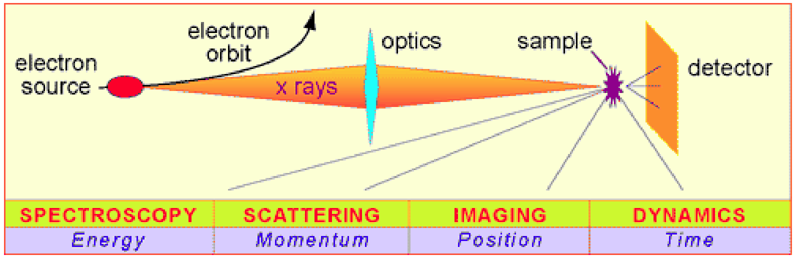


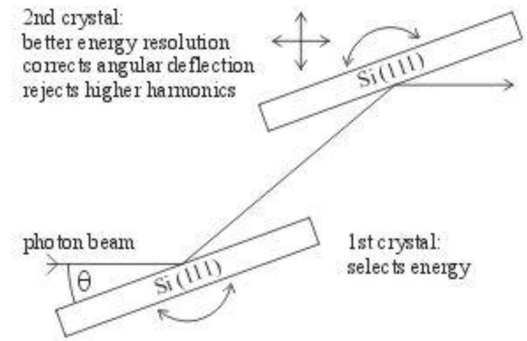
- Just for reference: Whenever an undulator moves, about 120-150 magnets are changed to compensate for the effect (slow+fast feed-forward, slow+fast feedback)

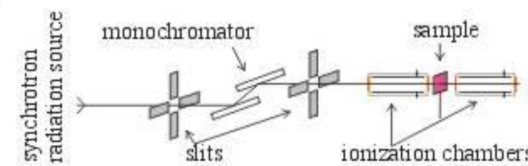
Beam Diagnostics: Position/Closed Orbit

- There are many reasons why good orbit stability is necessary:
- Accelerator Physics:
  - Changes in orbit cause changes in gradient distribution (e.g. horizontal offset in sextupoles) or coupling (vertical offset in sextupoles)
  - The dipole errors that cause the orbit changes directly create spurious dispersion (can lead to emittance increase, synchro-betatron coupling, deleterious effects from beam-beam interactions, …) or change the beam energy.
  - Photon beams can be missteered, resulting in damage.
  - Beam-beam overlap at interaction point.
- Users:
  - Stability of photon source point (flux through apertures, photon energy after monochromator, motion of beam spot on inhomogenous sample, …)
  - Stability of interaction point in colliders.

Why does the orbit/position need to be constant







- Without slits it is obvious that beam motion will t[illegible]slate to motion of photon beam on sample, i.e. different sample areas are measured
- Similarly in a monochromator without slits a vertical beam motion translates into a photon energy shift
- With slits, the effects get smaller and smaller with smaller slit size (there still are 2nd order effects because of the beam profile and the nonzero slit size). However, the smaller the slit the smaller the transmission and the larger the intensity fluctuations (and effects of slit alignment and motion).

Actual Beamline Example

- **Beamline 10.3.2 at the ALS**
- **Hard x-ray, microfocus, micro X-ray absorption or fluorescence, …**
- **Environmental samples (‘dirt’)**
- **Very heterogenous**

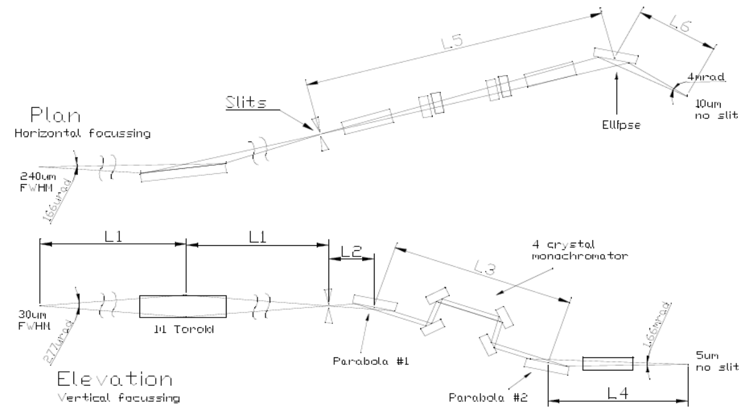
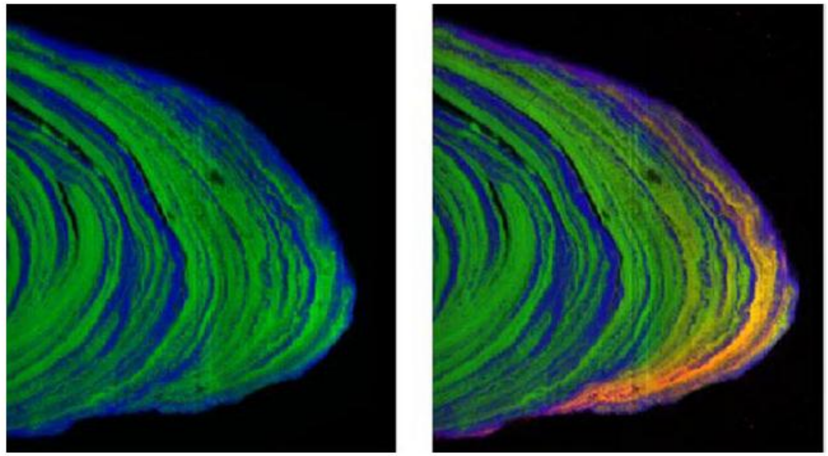


Figure 1. Optical layout. The dimensions L1..L6 and mirror types are as follows:



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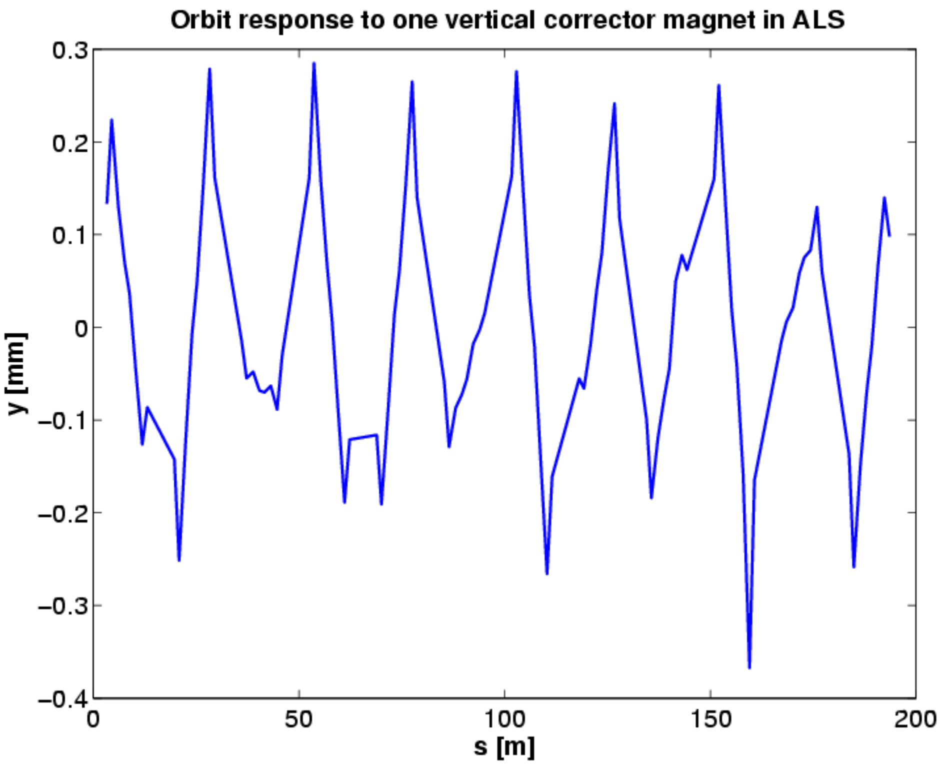
Closed Orbit: ‘Definition’

- The closed orbit is the (periodic) particle trajectory which closes after one turn around the machine (in position and angle) i.e. the fixed point in 4 (6) dimensional space for the one-turn map.
- The ideal orbit is the orbit through the centers of all (perfectly) aligned magnetic elements.
- Particles close to the closed orbit will oscillate around it.



Closed orbit errors

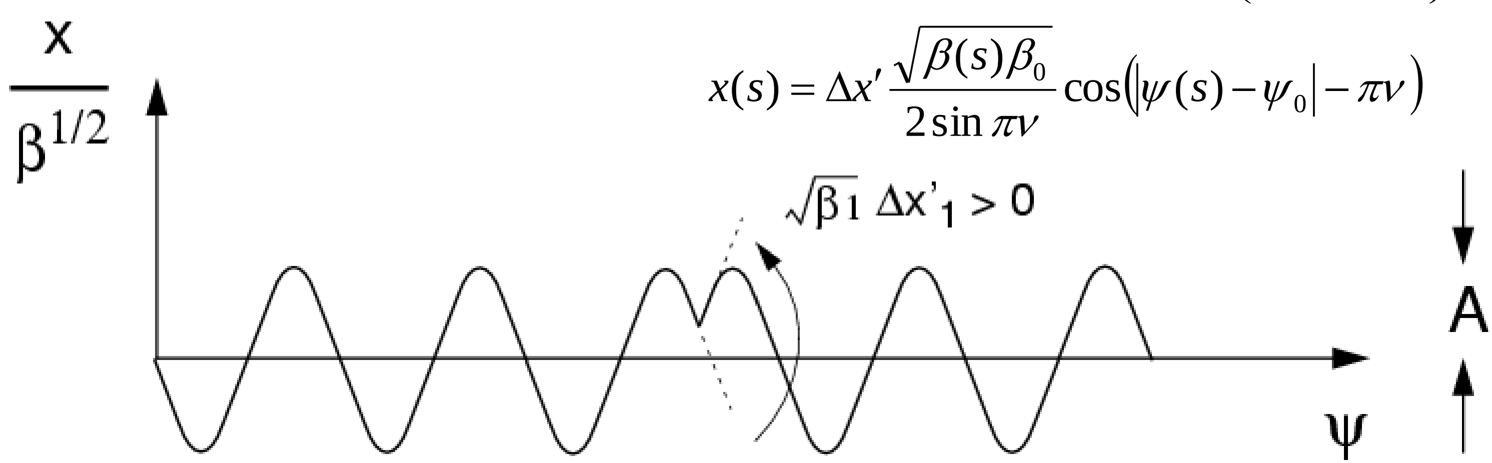
- **A single dipole error will create an orbit distortion which looks very simple in normalized coordinates:**

$$\begin{pmatrix} x_0 \\ x_0' - \Delta x' \end{pmatrix} = M_U \begin{pmatrix} x_0 \\ x_0' \end{pmatrix}$$

$$M_U = \begin{pmatrix} \cos 2\pi\nu + \alpha_0 \sin 2\pi\nu & \beta_0 \sin 2\pi\nu \\ -\gamma_0 \sin 2\pi\nu & \cos 2\pi\nu - \alpha_0 \sin 2\pi\nu \end{pmatrix}$$

$$\Rightarrow x_0 = \Delta x' \frac{\beta_0}{2\tan \pi\nu};\; x_0' = \frac{\Delta x'}{2}\left(1 - \frac{\alpha_0}{\tan \pi\nu}\right)$$

$$x(s) = \Delta x' \frac{\sqrt{\beta(s)\beta_0}}{2\sin \pi\nu} \cos\left(\left|\psi(s) - \psi_0\right| - \pi\nu\right)$$

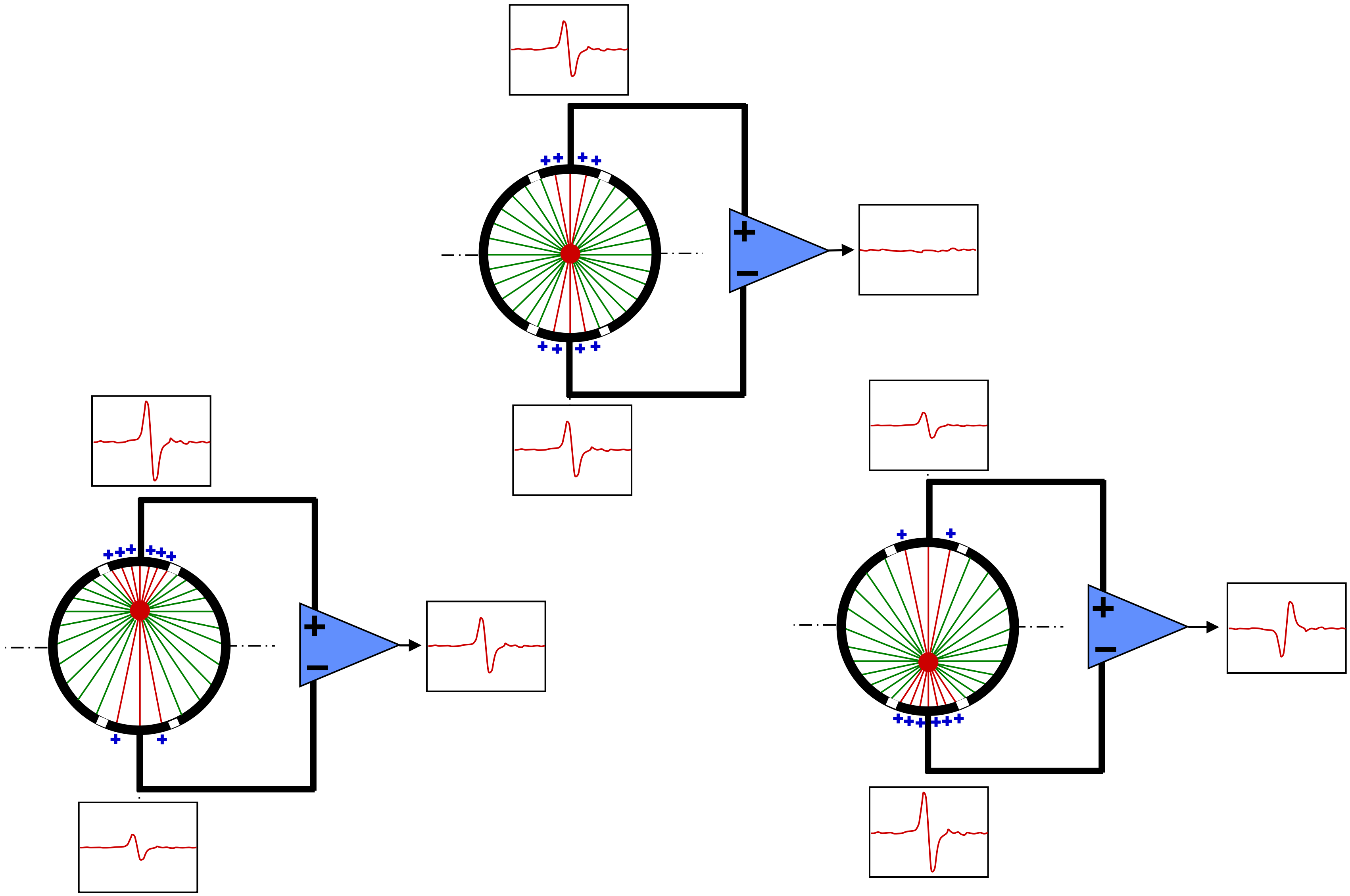


❖ The matrix containing the change in position at every BPM to a kick from every corrector magnet is called orbit response matrix. For an uncoupled machine it can be calculated (linear approximation) using above formula.

Measurement Methods

- Main categories are:
  - —Destructive/non destructive measurements
  - —RF/synchrotron radiation/scattering/absorbing based detection
  - —Pure position/profile measurements
  - —Fast/Slow (GHz-mHz)
- Linear accelerators and beamlines often use very different methods from storage rings
- Lepton accelerators often use methods different from hadron accelerators

Electromagnetic Beam Position Monitors



Capacitive Pickups

- **Standard method used at all 'high' energy storage rings**

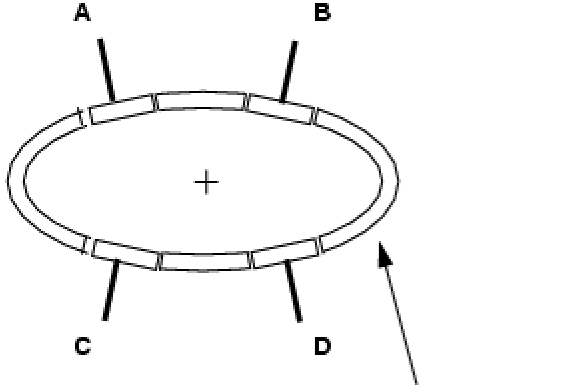
Charged Particle Beam Pickup Electrodes

Capacitive buttons

- Broadband, up to > 10 GHz
- Most effective when button diameter is comparable to the bunch length
- Minimal wakefield interaction with beam

$$X = K_x \frac{A-B+C-D}{A+B+C+D}$$

$$Y = K_y \frac{A+B-C-D}{A+B+C+D}$$

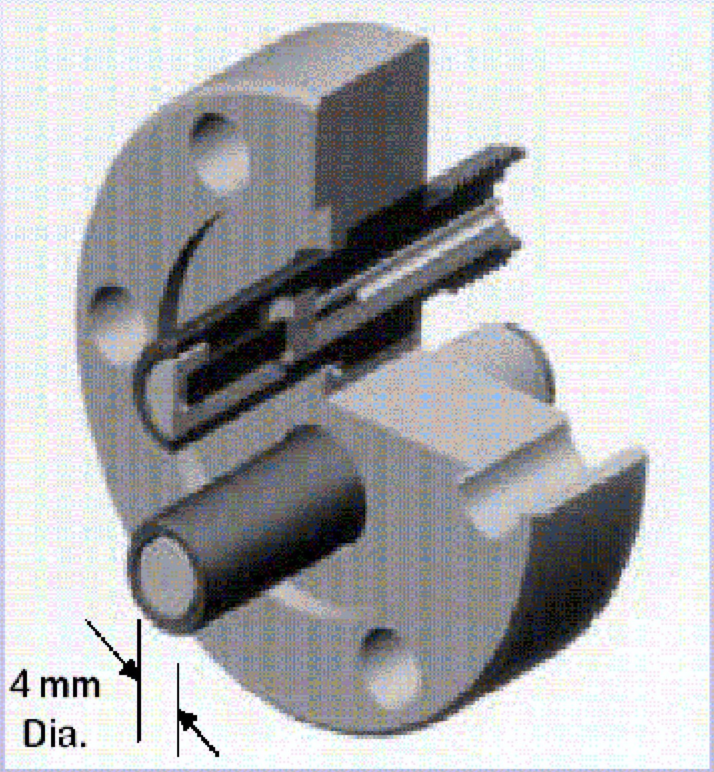


e.g. for round buttons of radius a in round pipe of radius r

$$Z_t(\omega) = V_p / I_b = \frac{a^2 \omega}{2 r \beta c} \frac{R}{(1 + j\omega RC)}$$

where $\beta = v / c$,
R = Transmission line impedance,
C = Button capacitance

Capacitive Pickups



Drawing courtesy J. Hinkson ALS

Electrical Specifications:

Frequency: DC to 20 GHz
Impedance: 50 ohm nominal, terminated by a capacitive button
Capacitance: 4.8 pF nominal
VSWR: 1.03:1 max. to 3 GHz, 1.15:1 to 20 GHz
Insertion loss: 0.1 db max. to 3 GHz, 0.5 db max. to 20 GHz
Matching: +/- 0.5 ohm in impedance, and +/- 0.1 pF in capacitance.
Connector: SMA female ,hermetically sealed with glass insulator.
Dielectric Strength: >1500 V at 50/60 Hz
Leakage Resistance: > 10^{13} ohm, from center conductor to outer housing

Mechanical Specifications:

Diameter: 4 mm
Materials: As per Kaman P/N 853881-001
Hermeticity: <10-11 cc He/sec
Radiation: >200 megarads gamma

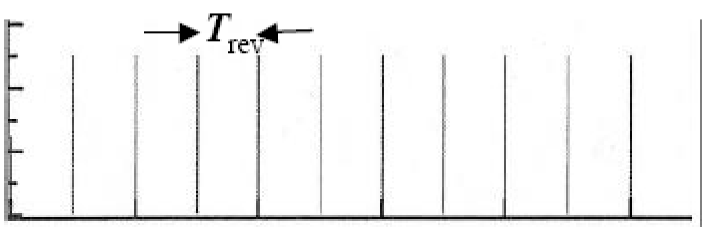
Bunch spectrum

Using a spectrum analyzer with a BPM can yield a wealth of information on beam optics and stability. A single bunch with charge q in a storage ring with a revolution time T_{rev} gives the following signal on an oscilloscope

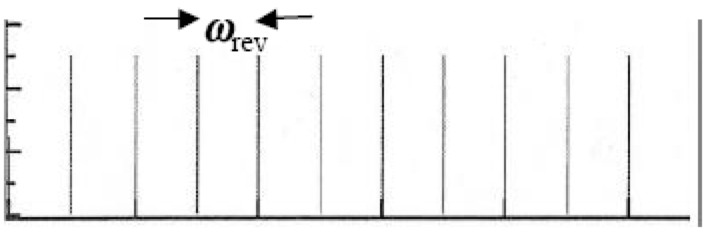
$$I(t) = \sum_{n=-\infty}^{\infty} q\delta(t - nT_{\text{rev}}),$$

where I'm assuming a zero-length bunch. A spectrum analyzer would see the Fourier transform of this,

$$I(\omega) = \sum_{n=-\infty}^{\infty} q\omega_{\text{rev}}\delta(\omega - n\omega_{\text{rev}})$$



Time

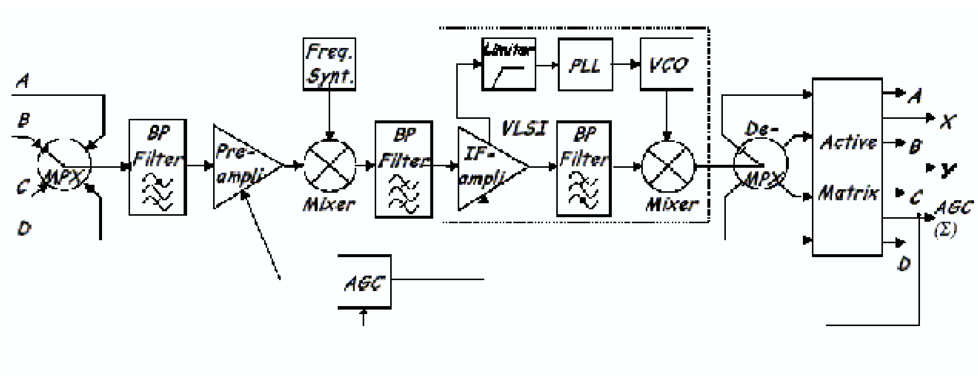


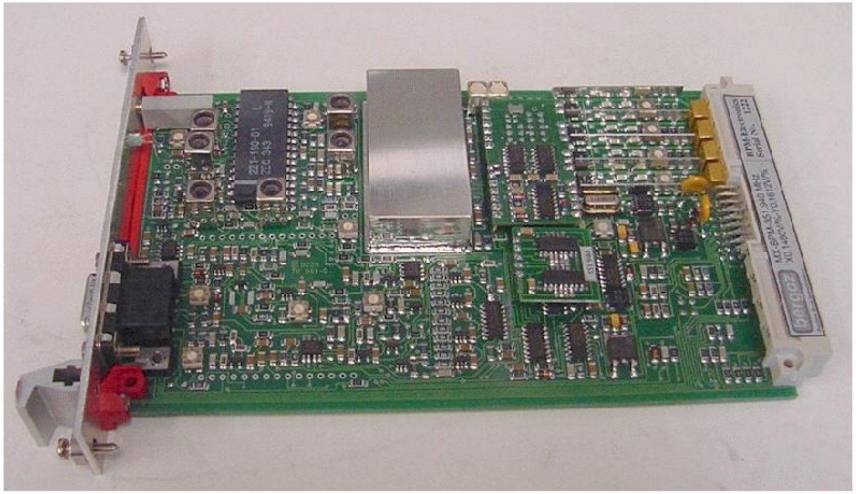
Frequency

Signal Processing Electronics

Bittner / Biscardi / Galayda / Hinkson/ Unser / Bergoz Narrowband Receiver

Normalization accomplished via multiplexing plus automatic gain control (AGC)*:



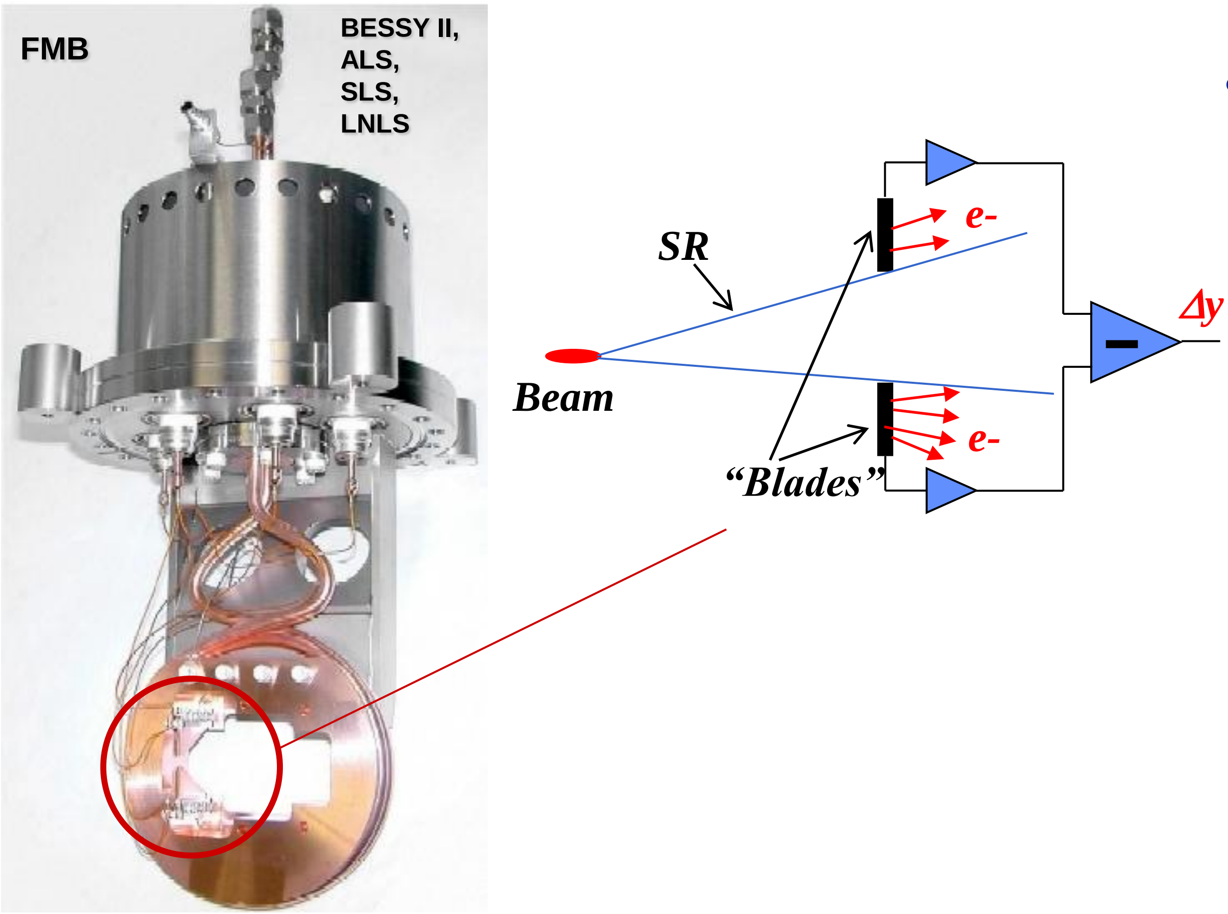


Typical F_{rf} = 60 to 800 MHz ,
Receiver IF bandwidth as narrow as a few hundred kHz
Position signal (X or Y) bandwidth a few kHz

* G. Vismara, DIPAC '99 http://srs.dl.ac.uk/dipac

Photon BPMs

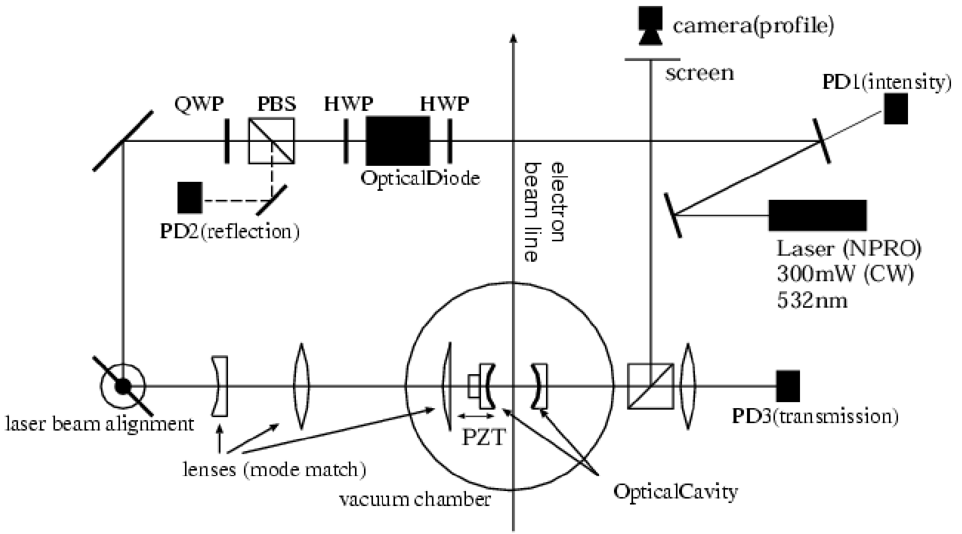
- **Synchrotron radiation is abundant in many accelerators – very useful for low noise, non desctructive position measurement**

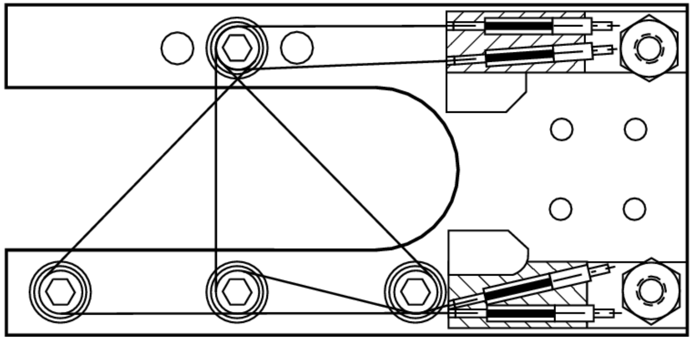


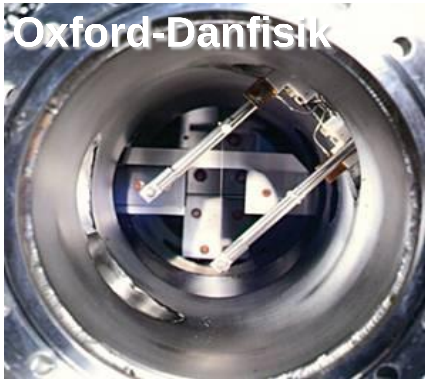
- **Work very well for dipoles in the vertical plane – for undulators OK for hard x-rays (with Decker distortions if undulators scan a lot), difficult for VUV, no solution for EPUs**

Wire Scanners/Flying Wires/Laser Wires/Screens

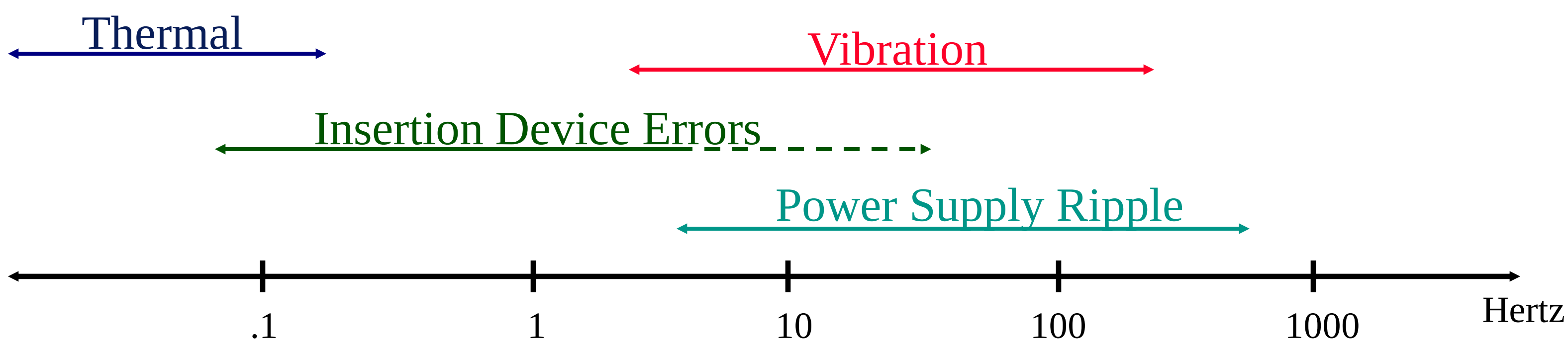
- Wire Scanners (SLAC/SLC) and screens are mostly used in beamlines and Linacs. Can achieve resonable high resolution but are usually destructive. Both can measure position and profile.
- Flying wires are less destructive and laser wires (KEK/ATF) are minimally destructive and provide excellent resolution (however they are slow)
- Some laser or interferometer based schemes achieve nm type resolutions.







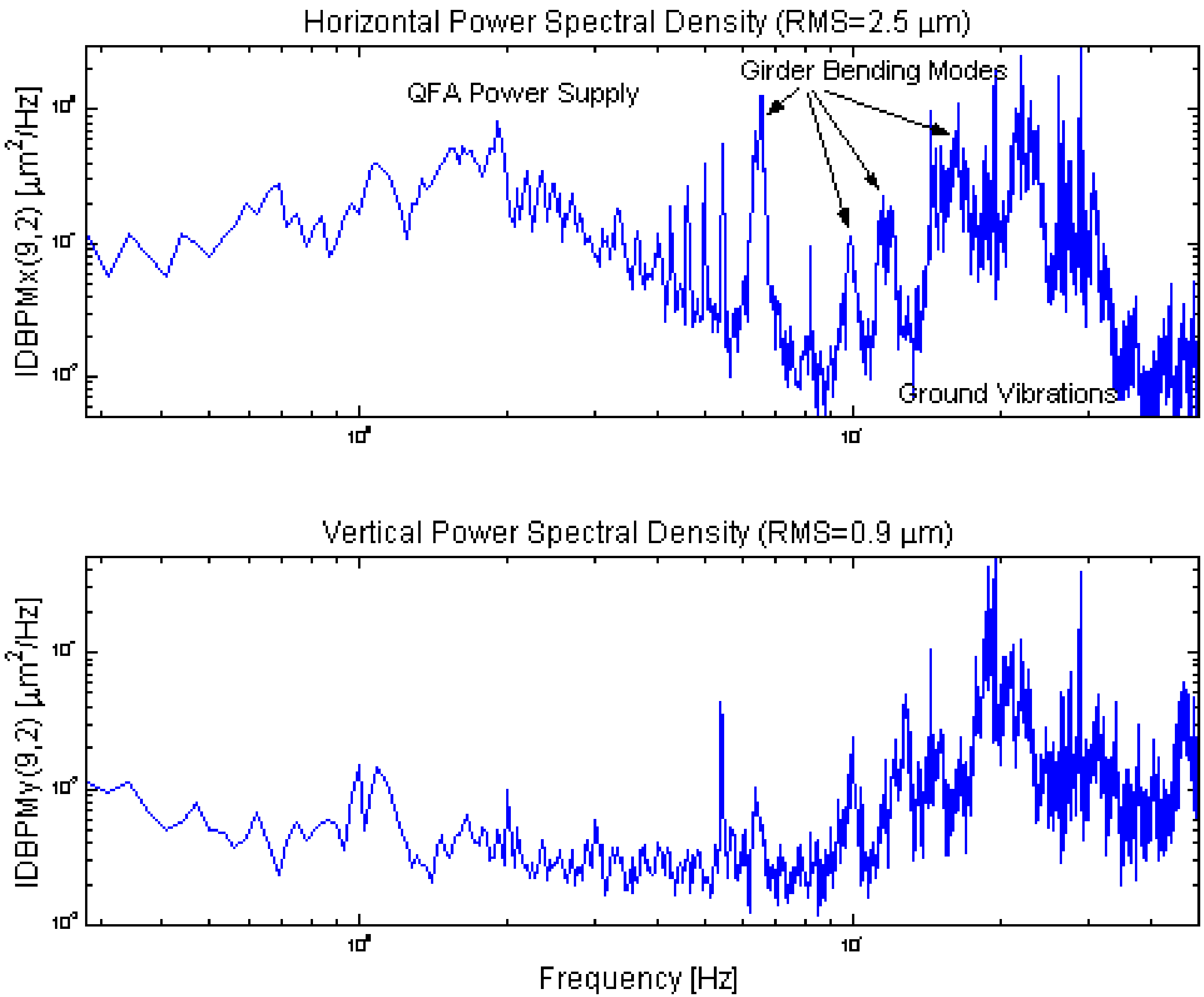
Causes for Orbit Distortions



Frequency	Magnitude	Dominant Cause
Two weeks (A typical experimental run)	±200 μm Horizontal ±100 μm Vertical	1. Magnet hysteresis 2. Temperature fluctuations 3. Component heating between 1.5 GeV and 1.9 GeV
1 Day	±125 μm Horizontal ±50 μm Vertical	Temperature fluctuations
8 Hour Fill	±50 μm Horizontal ±20 μm Vertical	1. Temperature fluctuations 2. Feed forward errors
Minutes	1 to 5 μm	1. Feed forward errors 2. D/A converter digitization noise
.1 to 300 Hz	3 μm Horizontal 1 μm Vertical	1. Ground vibrations 2. Cooling water vibrations 3. Power supply ripple 4. Feed forward errors

Beam Stability in straight sections w/o Orbit Correction, w/o Orbit Feedback, but w/ Insertion Device Feed-Forward

POWER SPECTRAL DENSITY



Data taken on 12-12-1999, during a 1.9 GeV user run at 278 mAmps

Orbit Correction

By measuring the orbit distortion in N BPMs along the ring, we find the set of displacements:

$$\mathbf{u}_N = \{u_1, u_2, \ldots, u_N\}$$

By using M correctors magnets, we can find a set of kicks that cancels the displacement of the beam at the BPM positions. This is obtained when:

$$-u_j = \frac{\sqrt{\beta(s_j)}}{2\sin(\pi\nu)} \sum_{i=1}^{M} \sqrt{\beta(s_i)}\ \theta_i \cos\nu\left[\left|\varphi(s_j) - \varphi(s_i)\right| + \pi\right] \qquad j = 1, 2, \ldots, N$$

Or in matrix representation, when:

$$-\mathbf{u}_N = \mathbf{M}\boldsymbol{\theta}_M \qquad with \quad M_{ji} = \frac{\sqrt{\beta(s_j)\beta(s_i)}}{2\sin(\pi\nu)} \cos\nu\left[\left|\varphi(s_j) - \varphi(s_i)\right| + \pi\right]$$

The kicks that need to be applied to the steering magnets for correcting the closed orbit distortion, can be obtained by inverting the previous equation:

$$\boxed{\boldsymbol{\theta}_M = -\mathbf{M}^{-1}\mathbf{u}_N}$$

The elements of the response matrix $\mathbf{M}$, can be calculated from the machine model, or measured by individually exciting each of the correctors and measuring the induced displacement in each of the BPMs.

Orbit Correction Methods

- Simplest method is the direct inversion of the orbit response matrix (in case of equal number of independent BPMs and corrector magnets).
- In case the numbers of correctors and BPMs do not match one can use least square correction (minimizing the sum of the quadratic deviations from the nominal orbit) often with the additional constraint (if solution is degenerate) to minimize average corrector strength.
- MICADO/MEC is a modification of the least square method. It iteratively searches for the single most effective corrector (starting with one up to the selected total number), calculates its correction strength using least square, finds the next most effective corrector, calculates the correction using those two via least square, …
- SVD uses the so called singular value decomposition. In this method small singular values can be neglected in the matrix inversion.
- Local Bumps allow to keep the orbit 'perfect' locally (sensitive SR user, interaction point, …) while relaxing the correction elsewhere.

Singular Value Decomposition

- **Any Matrix M can be decomposed (SVD)**

$$M = U \cdot S \cdot V^T = \sum_i \vec{u}_i \sigma_i \vec{v}_i^T ,$$

- **Where U and V are orthogonal matrices (I.e.** $U \cdot U^T = 1,\ V \cdot V^T = 1$ **) and S is diagonal and contains the (σ_i) singular values of M.**
- **Examples:**
  - **M is the orbit response matrix**
    - **U contains an orthonormal set of BPM vectors**
    - **V contains an orthonormal set of corrector magnet vectors**
  - **M is a set of many (single turn/single pass) orbit measurements**
    - **U contains an orthonormal set of spatial vectors**
    - **V contains an orthonormal set of temporal vectors**
- **Because of othogonality the inverse of M can be simply calculated:**

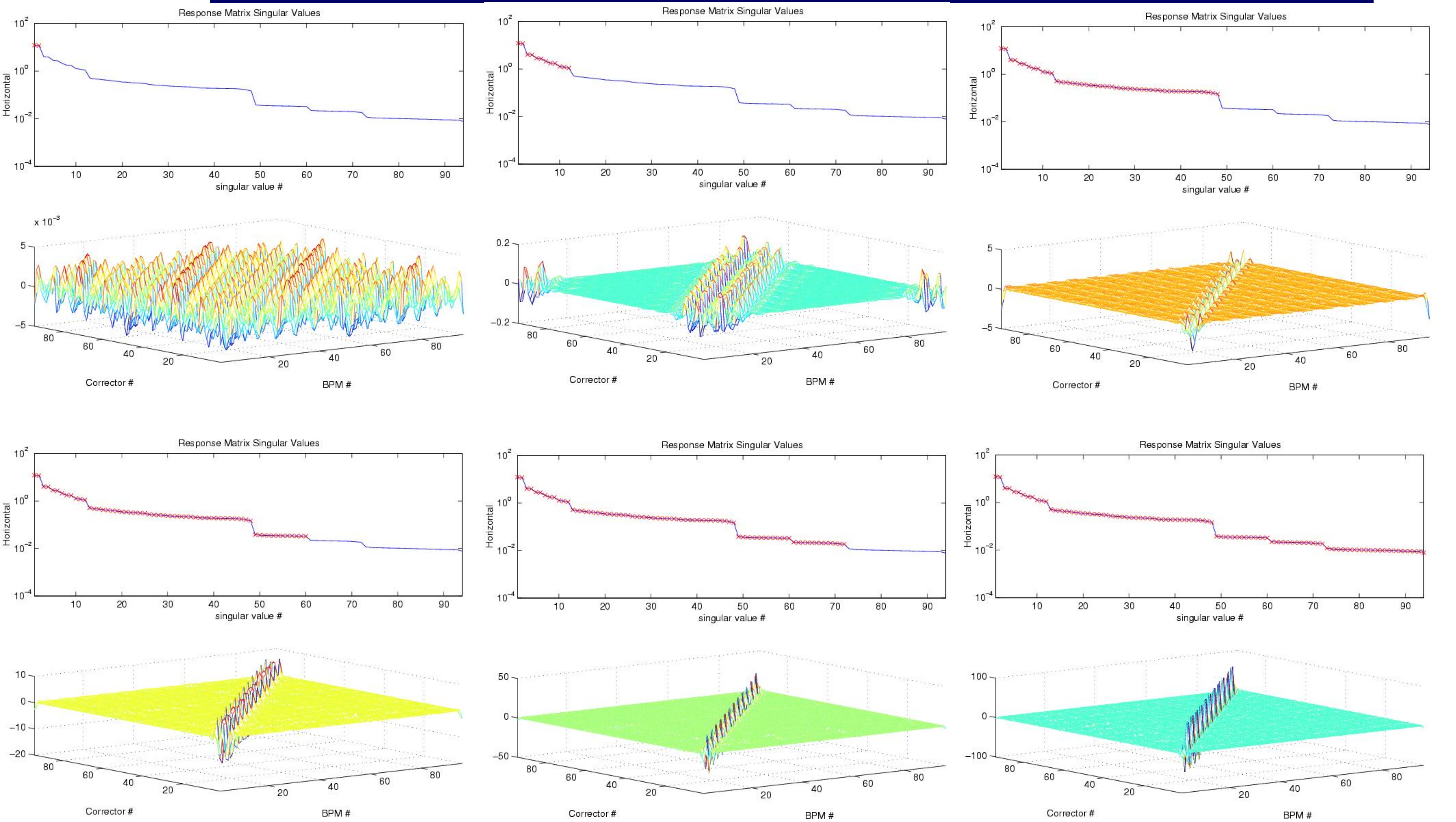
$$M^{-1} = \sum_i \vec{v}_i \frac{1}{\sigma_i} \vec{u}_i^T .$$

In case of very small singular values the inverse can be singular

Advantages of Correction Methods

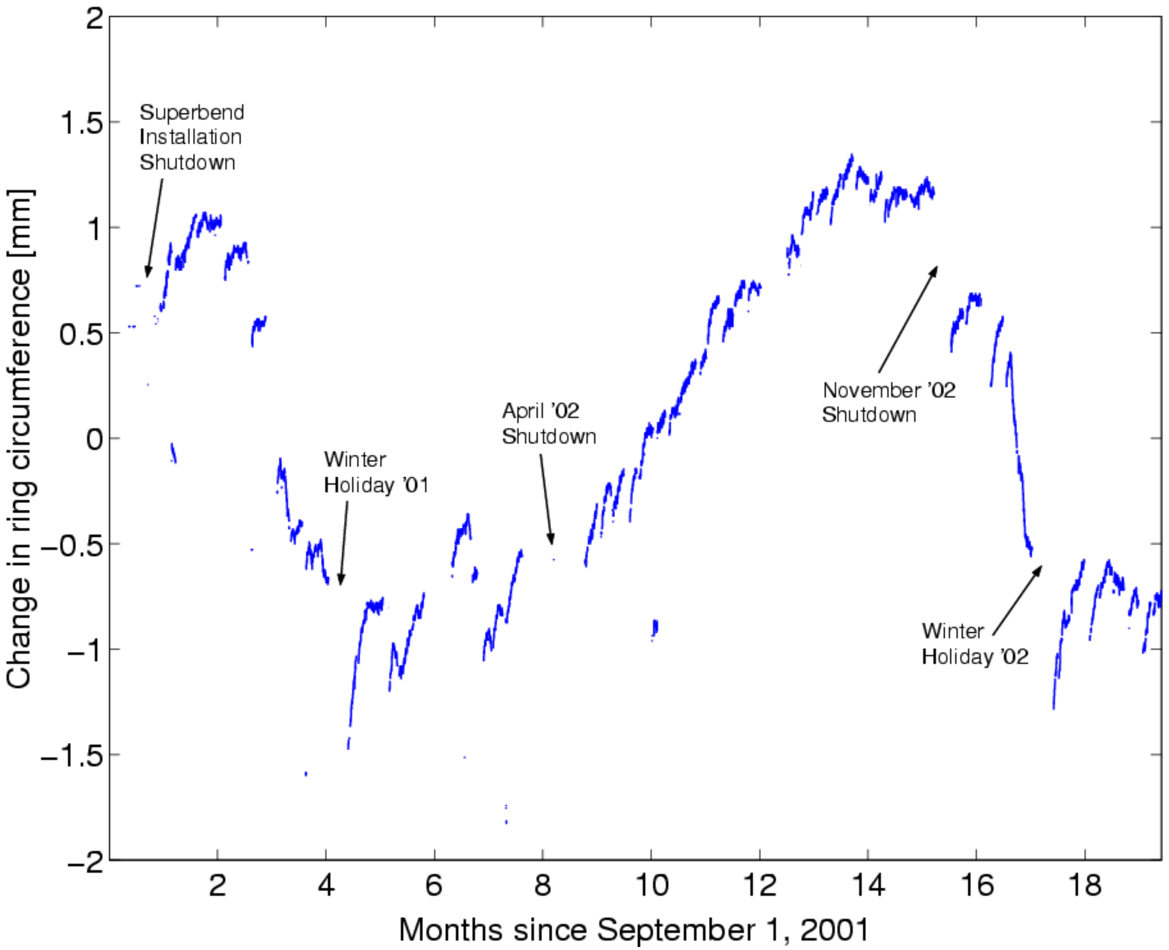
- Least square or direct matrix inversion
  - Disadvatages:
    - Have to trust every BPM reading
    - BPM and corrector locations very critical (to avoid unobservable bumps)
  - Advantages:
    - Minimizes OBSERVABLE orbit error
    - Works well for distributed/numerous errors
    - localizes the correction.
- MICADO
  - works well for few dominant errors (IR quads in colliders)
  - Does not allow good correction for many errors.
- SVD
  - allows to adjust behavior based on requirements.
  - Most light sources nowadays use SVD.

Example: SVD inverted matrix vs. number of Singular Values

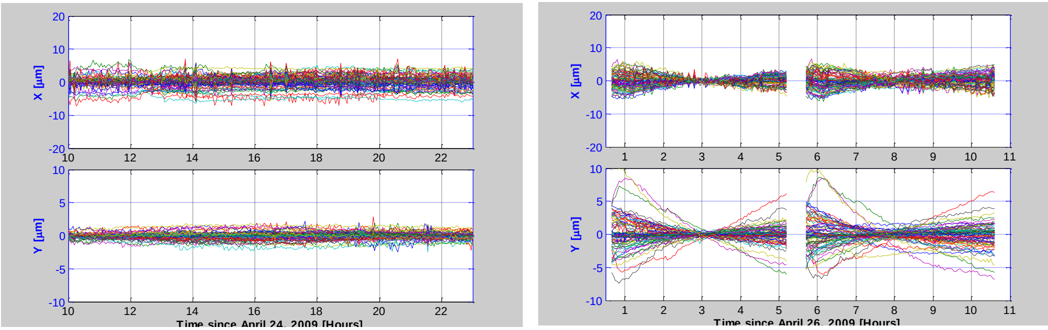


RF frequency feedback

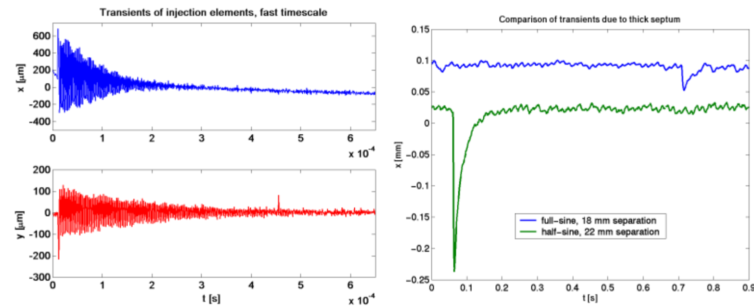
- Circumference of ring changes (temperature inside/outside, tides, water levels, seasons, differential magnet saturation, …)
- RF keeps frequency fixed – beam energy will change
- Instead measure dispersion trajectory and correct frequency (at ALS once a second)
- Can see characteristic frequencies of all the effects in FFT (8h, 12h, 24h, 1 year)
- Verified energy stability (a few 10^{-5}) with resonant depolarization



Top-off / Stability interplay with dynamic (momentum) aperture



ALS: mid term orbit stability (with+w/o Top-off)

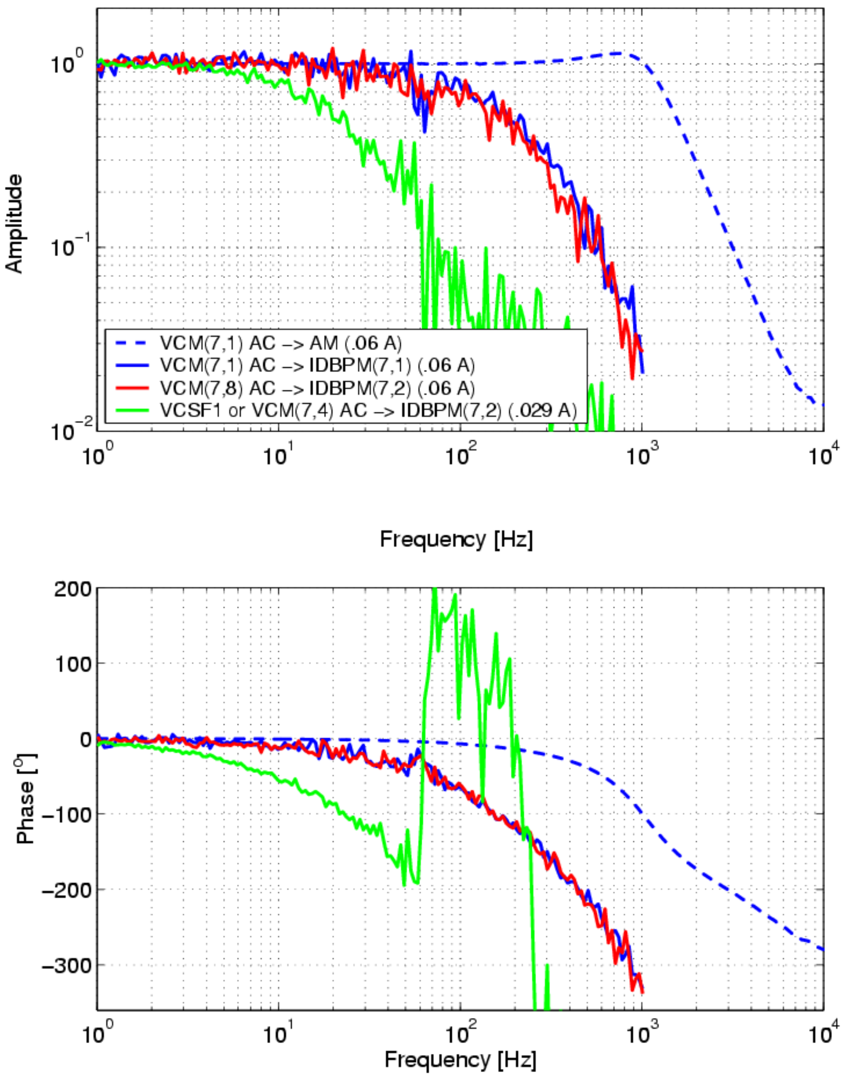


ALS: injection transients (fast+slow)

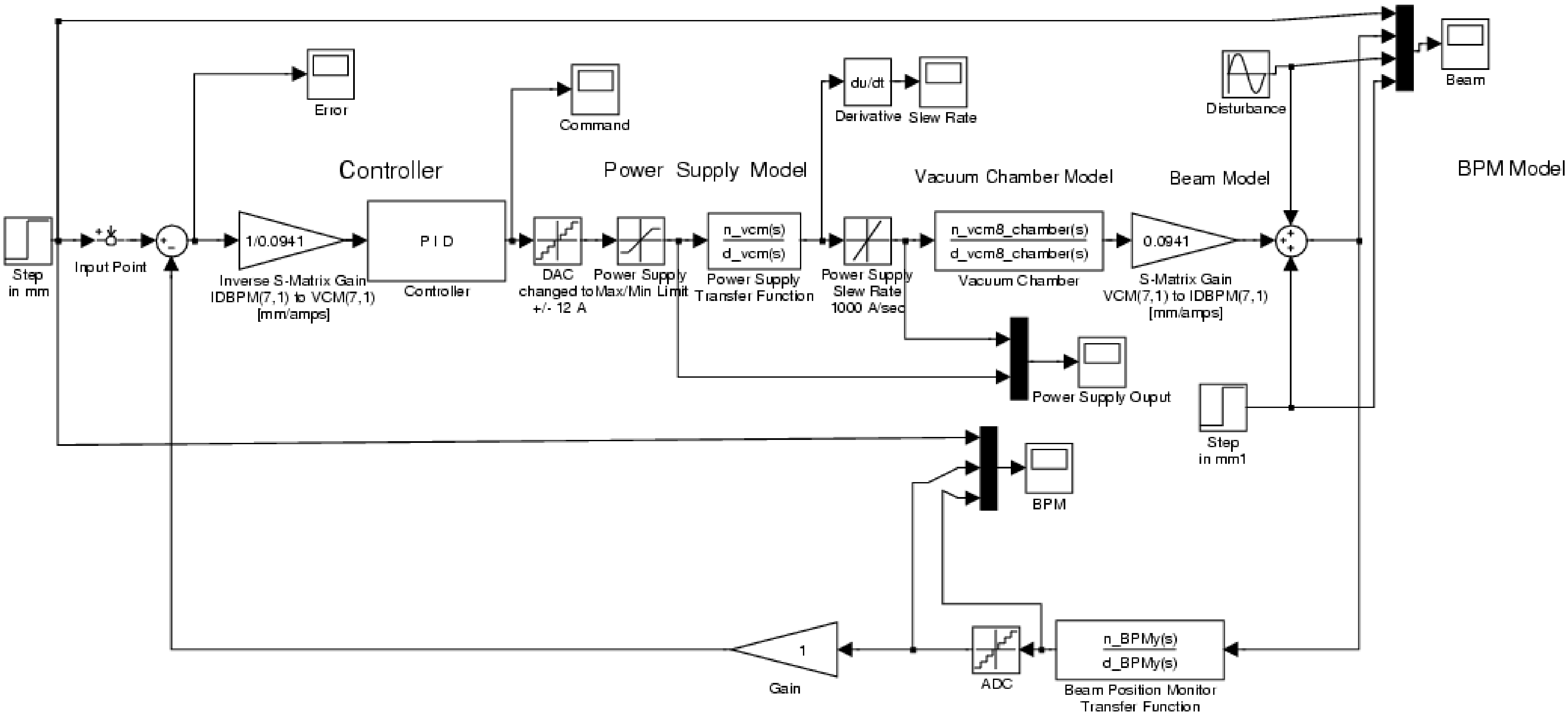
- **Top-off greatly improves the mid- and long-term stability (also for user beamline optics)**
  - **It does present some additional challenges in form of injection transients, however, currently the benefits greatly outweigh those.**
  - **Injection transients can be improved with better injection element design (magnets and pulsers), use of transverse multibunch feedbacks, or use of multipoles as injection kickers**
- **However, in top-off the dynamic (and momentum) aperture still has an effect on stability**
- **Insertion devices (for example EPUs) have the potential to substantially reduce the injection efficiency enough to reduce the stored current (this also can produce increased radiation dose rates).**
  - **Therefore keeping the nonlinear properties of the machine ‘stable’ remains important**

Fast Orbit Feedback

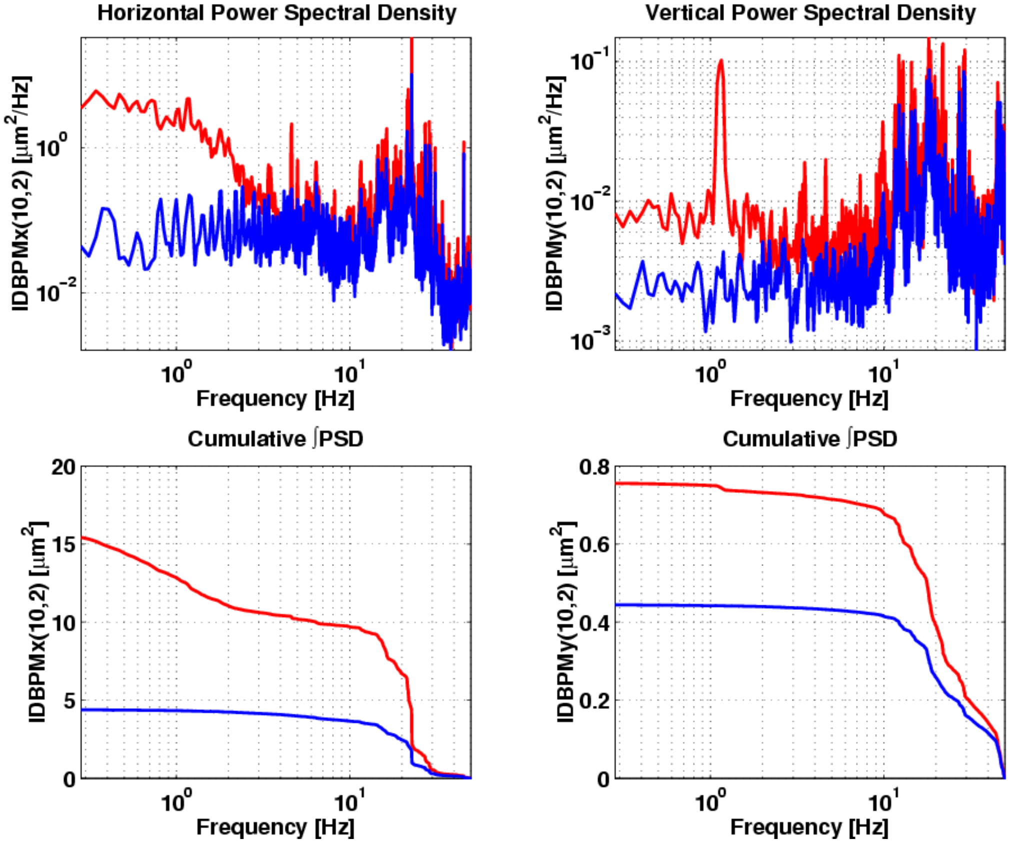
- **Time response of all elements becomes important!**
- **Controller type used is often PID**
- **System often are distributed (ALS 12 crates, about 40BPMs, 22 correctors each plane)**

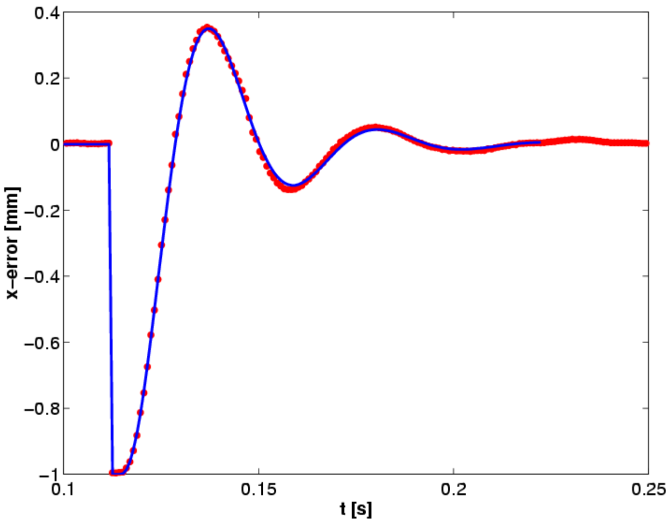


Simulink model of one channel of system



Performance of Fast Orbit Feedback at ALS



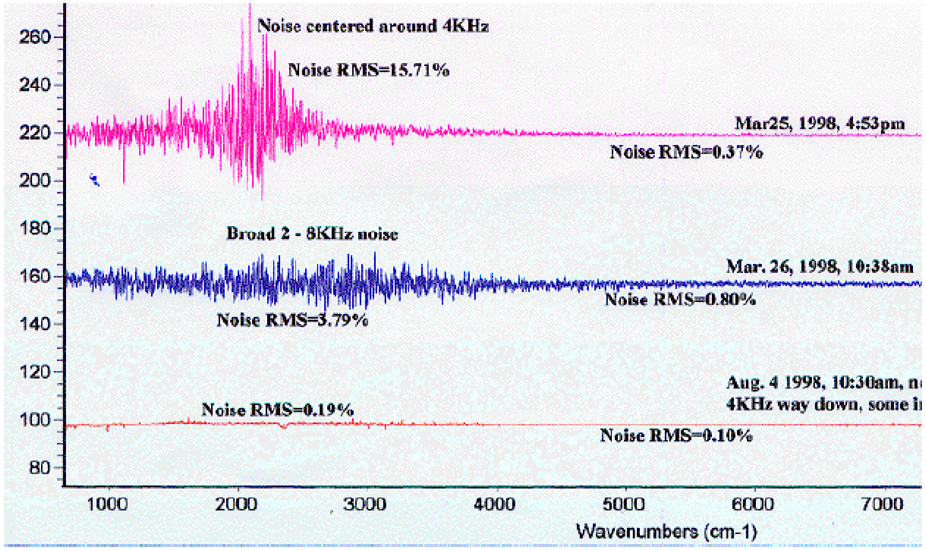


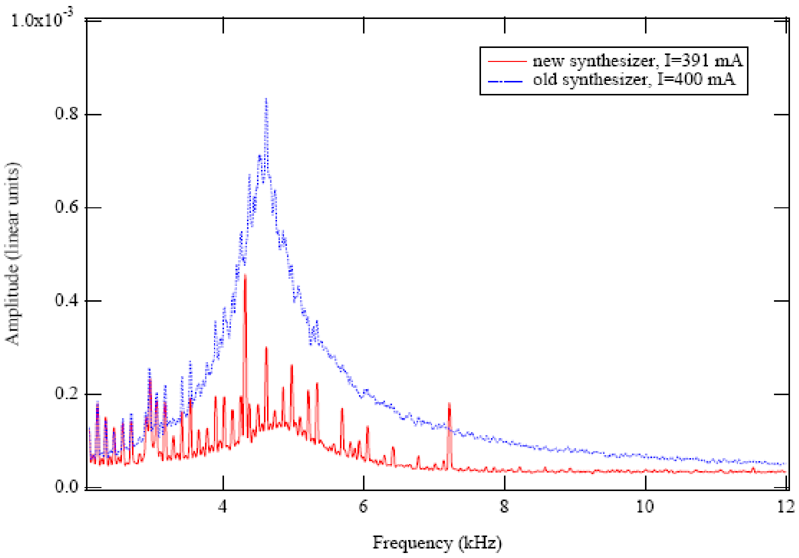
Comparison of orbit PSDs with and without fast feedback.
Fast orbit feedbacks are in use at several light sources: APS, NSLS, ESRF, (SLS)

Comparison of simulated (Simulink) and measured step response of feedback system in closed loop in a case where PID parameters were intentionally set to create some overshoot.

RF phase noise

- **Mode 0 motion nowadays is very small – 0.03 degrees rms**
- **Dominated by noise from master oscillator, rf distribution system, rf frequency correction … not HVPS**
  - **—Fast RF amplitude feedback reduces effect of HVPS to this level**
- **Use improved master oscillator + filtering at several points in low level RF frequency distribution system**



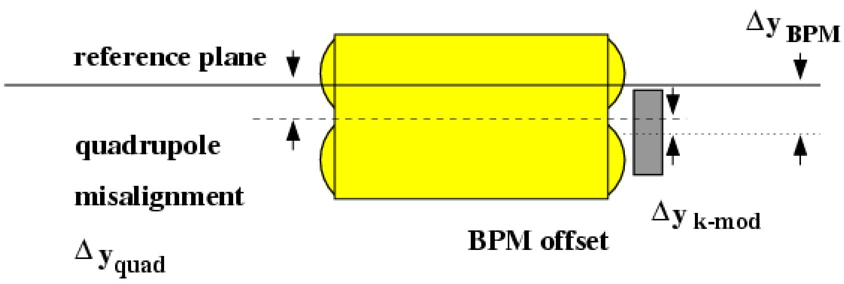


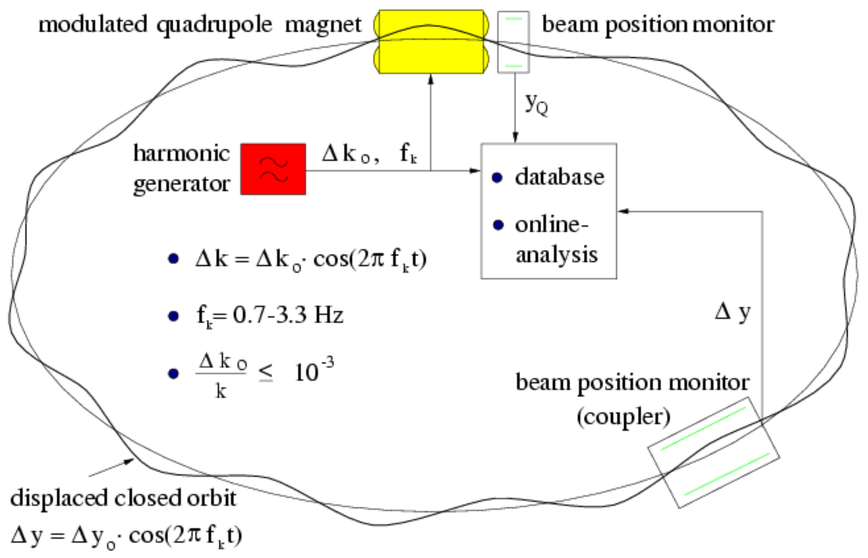
Beam Based Alignment

- To achieve optimum performance (dynamic aperture, beamsize, …) of accelerators, it is necessary to correct the beam to the center of magnetic elements
- Non centered beam can reduce physical aperture, and:
  - in quadrupoles: spurious dispersion, larger sensitivity of closed orbit to power supply ripple
  - in sextupoles: gradient errors (horizontal offsets), coupling errors (vertical offsets)
- Allows to link beam position (photon beams) to magnet alignment grid – helps to allow predictive optimum alignment of beamlines
- BPM centers are not known well enough relative to center of magnetic elements (vacuum chamber positioning, button positions, button attenuations, cable attenuations, signal electronics asymmetries, …)

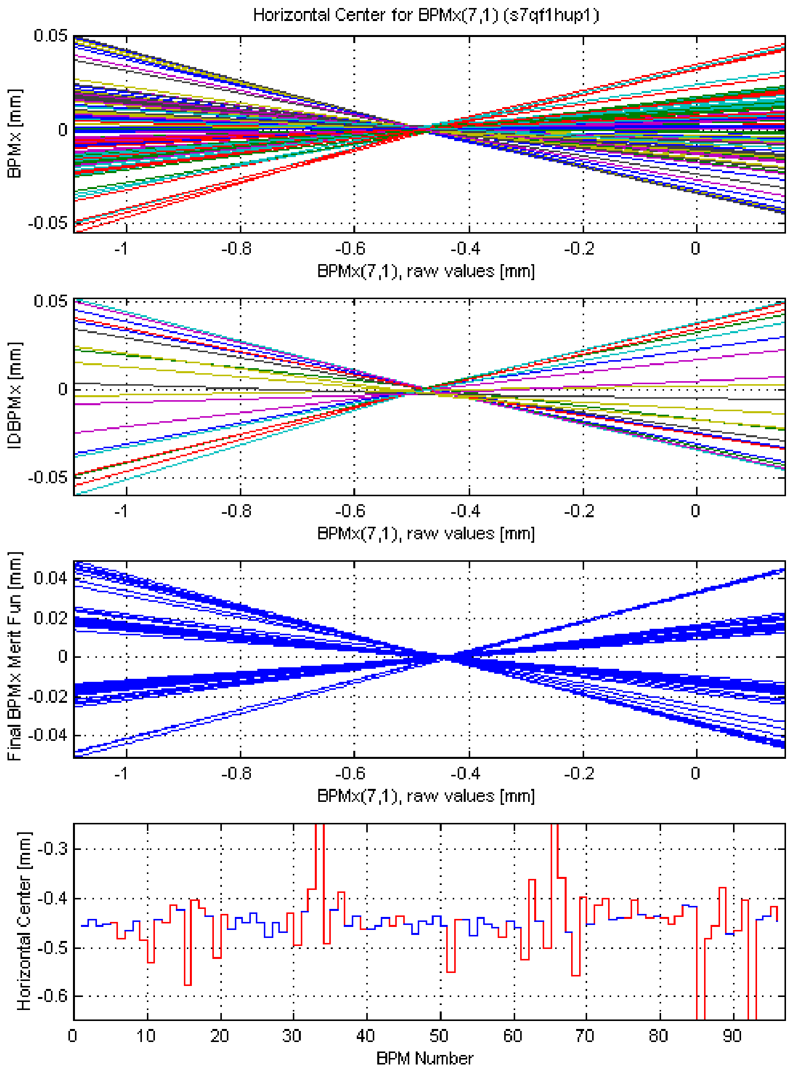
Beam Based Alignment

- BPM centers can be determined relative to adjacent quadrupole (or sextupole, skew quadrupole, using other techniques).
- Basic principle is that a change in quadrupole current will change the closed orbit if the beam does not pass through the quadrupole center.
- Sweeping the beam across a quadrupole and changing the quadrupole strength allows to find the centers.





Beam based alignment example: ALS



- All quadrupoles at ALS allow beam based alignment
- Automated computer routine – is performed regularly
- Main problem were systematic errors due to C-shaped magnets
- Offsets are fairly significant (rms of 300-500 microns) but very stable
- Beam based alignment only necessary after hardware changes or realignment
- Information from orbit response matrix analysis (with and w/o sextupoles) is in good agreement

Summary

- Stability (orbit, beamsize) is one of the most important performance criteria at accelerators
- Many different methods for position and size measurement exist, tailored to specific needs. Best resolutions are nm scale.
- Multiple noise sources perturb the beam.
  - —Passive noise reduction methods helps.
- Different correction algorithms are available. Advantages depend on the situation.
- Orbit feedbacks are used routinely, nowadays with several kHz update rate.
- Beam based alignment is essential to guarantee optimum performance of accelerators.

Further Reading (incomplete list):

- B. Hettel, Rev. Sci. Instr. 73, 3, 1396
- W.H. Press et al., Numerical Recipes, Cambridge U. Press (1988) p. 52
- Presentations at 2nd International Workshop on Beam Orbit Stabilization (2002): http://www.spring8.or.jp/ENGLISH/conference/iwbs2002/abstract.htm
- Presentations at the 3rd International Workshop on beam Orbit Stabilization (2004):

  http://iwbs2004.web.psi.ch/program/orals.html
- A. Friedman, E. Bozoki, NIM A344 (1994) 269
- J. Carwardine, F. Lenkszus, Proceedings of the 1998 Beam Instrumentation Workshop, http://www.slac.stanford.edu/pubs/confproc/biw98/carwardine.pdf